A STUDENT'S INTRODUCTION TO GEOLOGY

by G. M. Davies

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A STUDENT'S INTRODUCTION TO GEOLOGY

MAINLY PHYSICAL

BY

GEORGE MACDONALD DAVIES

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PREFACE

For the student beginning geology four things are needful —a lecturer who can expound and explain without killing interest; textbooks to supplement the spoken word; a laboratory containing good series of minerals, rocks and fossils and such equipment as maps and petrological microscopes; and access to cliffs and quarries, which are essential extensions of the laboratory. The first and second of these are equally important; for the student who relies on lectures alone may find difficulty in spelling common geological terms—one even wrote "new metallitic" when the lecturer, using the term for the *n*th time, omitted to spell pneumatolytic. On the other hand, reading by itself often leads to unusual pronunciations, such as "Sir Archibald Jeikie" for Geikie, and "gay noose" for genus.

There are several excellent textbooks on minerals, rocks, fossils, and historical geology; but it has long been difficult to recommend a modern introduction to physical geology. Geographers and geomorphologists have produced large and admirable accounts of the forces responsible for the structures and sculpture of the earth's surface, but they do not quite cover the needs of the beginner in geology. Moreover, they deal mainly with the scenery of America or New Zealand, and the English student needs a little encouragement to look about him in his own country.

In an attempt to satisfy this want the present book has been written. It is intended for the use of first-year students who have no previous knowledge of geology but who have some scientific background and are not deterred by the shorthand of a simple mathematical expression or chemical formula; but even these may be skipped if necessary.

Few students want to wade through turgid or nebulous writing, or to pay a high price for their books. Accordingly, the matter has been condensed as much as possible without

loss of clarity; and the illustrations are limited to figures in the text. Good half-tone plates are expensive, and their object is better attained by lantern slides demonstrated by the lecturer.

Again with a view to omitting unessentials, observations and theories are given here without mentioning the author's name in every case. This is a departure from modern usage, and perhaps from courtesy. But while an advanced student may want to know the history of his science, the beginner has little interest in the sources of his information, or in the godfathers and godmothers of the fossils he collects. An apology is here offered to any geologist who may feel aggrieved that his contribution to the temple of truth is not inscribed with his name but is incorporated along with those of past masters like William Smith, De la Beche and Lyell. There is a danger, too, that the student, with misplaced humility, may think "What is good enough for Professor Blank is good enough for me," or "Who am I to question Professor Dash's conclusions?". Whatever may be the function of authoritarianism in politics and religion, it should have no place in science. "Test all things" must be our ideal —though it is one that is impossible to attain.

A host of terms have been proposed by geographers on both sides of the Atlantic for the precise description of scenic features. Many of these seem unnecessary, and some a little absurd. Labels are useful things, but they do not in themselves add to our knowledge. Many of these terms are better omitted from a first-year course, burdened as it must be with unfamiliar words. But on the other hand a student may come across them, without any explanation, in his later reading. Perhaps the best plan is to give these words in brackets but not to use them.

The illustrations have been prepared by a number of different hands, and I must particularly acknowledge the drawings of fossils that embellish Chapter XXIV. They are by Mr. Maurice K. Wells.

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CONTENTS

CHAPTER I

THE SCOPE OF GEOLOGY

GEOLOGY is the science of *ge*, the earth, just as geography is the description of the earth's surface and geometry was in its origin a system of earth measurement, or land surveying. It deals with the rocks observed in the crust of the earth, and by inference with its interior; with the minerals composing those rocks; and the agencies that formed them, bent and broke them, and sculptured their surface into hills and valleys. It deals also with the fossil remains of animals and plants enclosed in the rocks, and endeavours to trace the history of the earth in as much detail as possible. And it applies the knowledge so attained to the discovery of useful minerals and rocks and to many other economic problems.

In pursuing this vast programme geology borrows freely from other branches of science, from physics and chemistry, zoology and botany, astronomy and mathematics; and a good general geologist should have some training in all these. It has also fostered certain ancillary sciences, such as mineralogy and palæontology, which may be pursued independently. Some acquaintance with Latin and Greek will help the student to understand most of the terms used in geology; while a knowledge of modern languages is essential if he is to keep up-to-date in the development of any branch of science. In his own language he must be able to express himself clearly and to read correctly what others have written, since it takes two to tell the truth. He should be something of an artist, if possible, as well as a photographer. In short, a wide general education is the best preparation for a geologist.

In the narrow sense of the term, geology is sometimes used for earth history, or stratigraphy, alone. But in the

wider meaning the subject includes the following main divisions:

1 COSMICAL GEOLOGY, dealing with the origin of the earth.
2 PHYSICAL GEOLOGY, dealing with the forces that cause denudation, deposition and uplift (dynamical), with structural features like folds and faults (tectonic), and with the origin of landscape (geomorphology).
3 MINERALOGY, including crystallography, crystal optics and descriptive mineralogy.
4 PETROLOGY, dealing with rocks, their composition and mode of origin.
5 PALÆONTOLOGY, dealing with the fossil remains of animals and plants (palæozoology and palæobotany).
6 STRATIGRAPHY, dealing with the history of the earth as recorded in the strata and their fossils.
7 ECONOMIC GEOLOGY, dealing with all economic aspects of the subject, such as ore deposits, coal, oil, water supply, sites of tunnels, dams and reservoirs.

A three-years course in geology may conveniently include divisions 1, 2 and 3 (above) in the first year, 4 and 5 in the second, 6 and 7 in the third. But a purely academic syllabus may pay very little attention to 7.

CHAPTER II

COSMICAL GEOLOGY

GEOLOGY deals with the solid rocks, and its methods are not applicable to the earliest periods of the earth's history, when the rock materials were still molten or gaseous. It is to the astronomers, mathematicians and physicists that we turn for information about the earth's origin. Other planets prob-

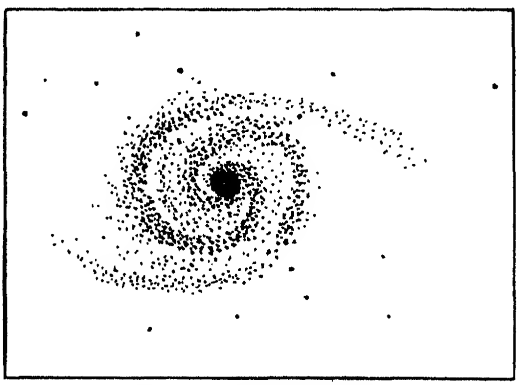

FIG. 1. A Spiral Nebula.

ably originated in the same way as the earth; and some other stars may have had a similar history to the sun.

Laplace, in framing his nebular hypothesis (1796), thought the planet Saturn gave a clue. He assumed the matter of the solar system existing as a mass of highly heated gas occupying a very large space and rotating about an axis. As it cooled it contracted and therefore rotated faster, the momentum being unchanged. So it became more and more oblate until the equatorial bulge broke away to form rings like those of Saturn, and the rings condensed

into planets. The nebulæ were thought to show stages in the evolution of planets from parent stars.

The planetesimal theory of Chamberlin and Moulton started with small solid bodies, condensations of matter drawn from the sun by a passing star, called planetesimals, which on falling together were fused by the heat of impact.

But neither of these theories is tenable. Saturn is unique, as far as we know, and should not be taken as a pattern of normal planetary evolution. With increasing angular velocity a mass of gas will give off matter at the equator, and at opposite ends of an equatorial diameter if there is any external gravitational field, that is, any attraction toward other

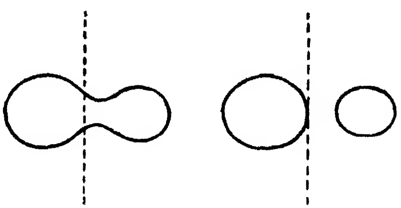

FIG 2. Evolution of a Double Star.

stars. This matter will continue to rotate with the nucleus and form spiral arms as in many nebulæ. But the central mass of gas must be large, as it is in the nebulæ, which are of a different order of magnitude from the stars. Their condensations are stars in the making, not planets, and their evolution probably leads to star clusters. In a mass no greater than the solar system the gas would escape into space, gravitation being insufficient to retain it. Only if it came away rapidly would it continue to revolve about the sun.

Again, a rotating mass of liquid, with increasing velocity, would form first a pear-shaped body and then two separate bodies, one larger and one smaller, but not comparable to sun and planet or planet and satellite. Binary stars seem to have originated in this way: they were not liquid, but they had not the required degree of central condensation to behave otherwise.

At present only Jeans' tidal theory, or some variant of it, appears to be tenable. The fixed stars are really in motion, and one of them may have approached near enough to the primitive sun to have raised strong tides by its gravitational pull on the rotating gas. As the star came nearer the tidal bulge broke away, first in a thin stream, then increasing till the closest point was reached, and diminishing as the star

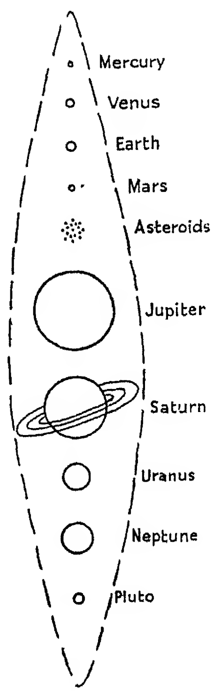

FIG. 3. Diagram to illustrate the Birth of the Planets.

receded. The matter so drawn off condensed to form the planets, and their sizes are conformable with the theory, though of course that does not prove it. The outermost planets, Pluto, Neptune and Uranus, are smaller than the intermediate ones, Saturn and Jupiter, while Mars, Earth, Venus and Mercury are smaller again.

Some idea of the relative sizes of the heavenly bodies may be obtained if we imagine the earth's orbit reduced to the size of a halfpenny, one inch in diameter. The sun would then be represented by a small grain of sand at the centre of the coin and the earth by an invisible speck of dust on its edge. The nearest fixed star would be as another sand grain four miles away, a nebula perhaps the size of an English county, and the Milky Way the circumference of the earth. Space is not congested, and the development of planetary systems by tidal encounters cannot be a common occurrence. But in the early days of an expanding universe the stars were much closer together and the chance of such encounters was very much greater. There is indeed evidence suggesting that the formation of the universe was not long antecedent to the birth of the planets and that the age of both is of the order of two or three thousand million years. The fossiliferous rocks represent only about a quarter of that period.

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CHAPTER III

GEOLOGICAL TIME

ARCHBISHOP USSHER'S chronology placed the creation of the earth about 6,000 years ago, and so long as it was accepted geological evidence meant nothing. The sedimentary rocks, even though their total thickness is many miles, were attributed to the Noachan deluge, and the fossils in them were held to be sports of Nature or due to some mysterious generative force of the earth.

It is clear that the deposition of the sedimentary rocks, like the evolution of their faunas, must have taken many millions of years. The relative thickness of the rocks of the different Systems may give an idea of the relative duration of the Periods in which they were deposited; and if we had a reliable estimate of the average time necessary to form one foot of sandstone, clay or limestone, we could find this duration by a simple multiplication sum. Even this (which has been attempted) makes no allowance for breaks in deposition, or the unknown thicknesses that have been eroded. The geological record may be not unlike a net—a series of gaps held together by string.

Attempts have also been made to find the age of the ocean by estimating the amount of sodium it contains and dividing that figure by the amount of sodium brought in by rivers in a year. The result, about one hundred million years, is quite unreliable. It assumes that the primæval ocean was fresh water, and there is no reliable estimate of the sodium withdrawn from the ocean to form our salt deposits, or included in the sediments by adsorption and base exchange. Moreover, rainfall, erosion and river action are certainly greater now, when there are so many lofty mountains of relatively recent origin, than during the long geological periods of denudation unbroken by uplift.

Lord Kelvin attacked the problem of the age of the earth by calculating the rate of loss of heat, as shown by the temperature gradient of the rocks. He concluded that the crust must have been at a temperature at which rocks melt about 20 or at the most 40 million years ago. There seemed no avoiding his conclusions on the data then available; but geologists could not accept them.

A new factor, which upset Lord Kelvin's results, came to light when radioactive elements were discovered. It is now known that uranium and thorium in particular are continually giving off atoms of helium, with the evolution of heat; and though these elements are not common in the rocks, the total heat evolved is considerable. Joly claimed that it exceeds the loss of heat by radiation and that the crust of the earth is normally growing hotter instead of colder. There is also the heat effect of the far commoner but feebly radioactive elements, such as potassium.

One effect of radioactive minerals is to produce pleochroic haloes in certain minerals such as biotite. Thus tiny zircon crystals enclosed in biotite are surrounded by spheres of darker biotite; and these spheres have radii of either 34.4 microns* or 42.5 microns, which are the ranges of the helium atoms ejected by the uranium and thorium families respectively. The radii do not vary with age; but the depth or colour of the haloes depends on the intensity of the radioactive source and the age, just as the darkness of a photograph depends on the intensity of the light and the length of exposure. Artificial haloes may be induced in biotite by exposing it to high concentrations of radioactivity for a short time; and if natural haloes are found that exactly match them we may conclude that the lengths of exposure in the two cases are inversely proportional to the radioactivity. The difficulty of estimating the radioactivity of the minute zircons causing natural haloes prevents this method from giving reliable results.

The longer uranium and thorium have been decaying in a rock the greater will be the amount of their end-products, helium and lead. The rate at which these are formed is

* 1,000 microns = 1 millimetre.

known. Helium is a gas and is liable to escape if the rocks are heated; but in basalts which have been neither metamorphosed nor weathered the amount of helium present seems to be nearly the amount that has been produced since the rocks were molten. In the case of highly radio-active material, such as pitchblende or thorianite, the amount of lead present, in proportion to uranium and thorium, gives a more reliable figure. The simplest formulæ for the age, t, are $t = \frac{He}{U + .27\ Th} \times 8.8$ million years, and $t = \frac{Pb}{U + .36\ Th} \times 7{,}600$ years, where He, Pb, U and Th are the percentage of helium, lead, uranium and thorium found by chemical analysis.

These methods, based on the helium and lead ratios, are the most accurate so far available. They have been used to find the age in years of rocks and radioactive minerals whose geological age is known; and they enable one to assign approximate limits, in millions of years, to the geological Periods. Thus a basalt of Pliocene age has been found to be 13 million years old, and a basalt from the Cambrian 465 million years. Meteorites have given ages from 100 to 2,800 million years.

There may, however, still be many unknown factors vitiating these figures for the absolute age of a rock; and geologists continue to use their relative time scale of Eras, Periods, Epochs and Ages,* with the corresponding rock divisions into Groups, Systems, Series and Stages,* based on the order of superposition of the rocks and recognised by their characteristic fossils. The table below shows the names of the Periods (or Systems) and their approximate duration according to Professor Schuchert's estimate; while their relative lengths are indicated in the figures on pages 187 and 188.

* See also pages 187-189.

THE GEOLOGICAL PERIODS

Eras	*Periods*	*Duration in millions of years*	*Age in millions of years.*
Cainozoic (Tertiary)	Recent and Pleistocene	1	1 to 0
	Pliocene and Miocene	24	25 to 1
	Oligocene and Eocene	35	60 to 25
Mesozoic	Cretaceous	60	120 to 60
	Jurassic	25	145 to 120
	Triassic	25	170 to 145
Palæozoic	Permian	40	210 to 170
	Carboniferous	75	285 to 210
	Devonian	40	325 to 285
	Silurian	25	350 to 325
	Ordovician	60	410 to 350
	Cambrian	90	500 to 410
	Pre-Cambrian	Perhaps 1500 or more	?2000 to 500

One more point may be mentioned. Life wherever we find it, in plant or animal, is always associated with the substance called protoplasm, and this is stable through a limited range of temperature. Yet the surface of the earth has been maintained within those limits for over 500 million years by a mechanism unimagined by the physicists of the nineteenth century.

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CHAPTER IV

IGNEOUS ROCKS

ROCKS may be divided into three main classes according to their mode of origin:—

IGNEOUS, which have solidified from a state of fusion, either at the surface of the earth (volcanic) or beneath it (intrusive).
SEDIMENTARY, which have been formed, generally under water, from fragments of older rocks, or by chemical or organic agency.
METAMORPHIC, which have had their nature changed by heat and pressure, but without fusion.

Basalt and granite are the two most widespread igneous rocks, and for many years there was controversy between the Neptunists and the Plutonists as to their origin. The Neptunists, led by Werner, claimed that basalt was formed in the sea, like the shales and sandstones associated with it. They pointed out that it forms extensive sheets, not like the narrow lava streams with which they were familiar, and that it usually shows no scoriaceous crust or steam cavities, while it often contains hydrated minerals which are not stable at high temperatures. But what clinched the case in favour of the Plutonists was the fact that basalts frequently transgress, or pass abruptly from one horizon to another (see *Fig.* 12, p. 21), and no marine deposit can do this. Actually, some basalts have reached the surface as lavas, by fissure eruptions or otherwise, and others have forced their way along the bedding planes or across them as intrusions.

The case of granite is somewhat different. It was recognised that granites have the same chemical composition as some lavas (rhyolites), but they differ from rhyolites in texture and in the absence of glass. Rhyolite was thought to be formed from fused granite, and granite was assumed to be the oldest rock on earth, the first solid crust.

Granites have not the form of lava flows and are not commonly associated with volcanic rocks. Moreover, the felspar of granites is in well-formed crystals which must be earlier

than the quartz filling the space between them; but quartz has a higher melting point than felspar and so might be expected to crystallise out first from a molten magma* as it cooled. The magma, however, is not a pure melt but a mixture, and the order of crystallisation depends on the proportions of the different minerals in it, not on their melting points when pure.

Here, too, the argument was decided in favour of the Plutonists by the branching veins or apophyses connected with granite masses and by the alteration (metamorphism) of the surrounding rocks by heat and pressure. Granites represent large bodies of magma which remained at a depth where the rocks are hot, and cooled there very slowly and under high pressure. The volatile fluxes, chiefly H_2O and CO_2, were retained, keeping the magma fairly fluid, and the atoms were free to build up large crystals. Smaller bodies of a similar magma crystallising nearer the surface (hypabyssal or minor intrusions) cool faster and their texture is not so coarse as in the granites. They form microgranites and quartz-porphyries. If the magma reaches the surface it cools still more rapidly and most of the volatile fluxes are lost. It becomes highly viscous and the crystals are small, and there is often much glass. It then forms volcanic rocks such as rhyolite, pumice and obsidian. There is a continuous series among rocks of granitic composition from coarse-textured granites to volcanic glass.

Granites are not found among the most recent sedimentary or volcanic rocks because it takes a considerable time for denudation to remove the overlying rocks and expose the granite.

Igneous rocks can thus be divided into three groups, based on texture and mode of origin; but there are no sharp lines of division, only a continuous variation.

PLUTONIC. Large deep-seated masses, coarsely crystalline and without glass.
MINOR INTRUSIONS. Finer textured. Sometimes called hypabyssal.
VOLCANIC. Fine textured and often glassy.

In addition there is a practically continuous variation in

* Magma, meaning a pasty mass, is the term used for the fused material which has yielded the igneous rocks and also the volatile fluxes and residual liquids which helped to keep it fluid.

mineral and chemical composition, the two being interdependent. The granites are characterised by a high silica content, usually 70% or more, and this expresses itself in the presence of abundant free silica in the form of quartz. This silica content is taken as the basis for classification; rocks with much silica in proportion to the bases (Al_2O_3, Fe_2O_3, FeO, MgO, CaO, K_2O, Na_2O, etc.) are called acid rocks and those with little silica basic. Intermediate rocks may be described as sub-acid or sub-basic, and certain rocks are spoken of as ultrabasic. Their mineral characteristics are shown in the table on page 14, with the names of the commonest rocks

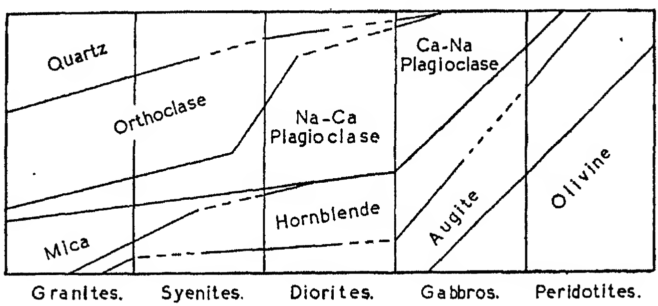

FIG. 4. Mineral Composition of the Plutonic Rocks.

in each class of plutonic, hypabyssal or volcanic origin. The specific gravity, G, is also given; it increases from the acid to the ultrabasic and is less for a glassy rock than for a crystalline rock of like composition.

Any comprehensive study of rocks presupposes a knowledge of the rock-forming minerals. The geologist must first be a mineralogist. Only the most important minerals are mentioned here, and the student should endeavour to make himself familiar with their appearance in hand-specimens and under the microscope.

The essential minerals of igneous rocks can readily be divided into two groups, one light coloured and the other dark. The former is known as the felsic group, a term coined on Lewis Carroll principles from the *fel*spars, *fel*spathoids and *si*lica (quartz) which compose the group. The latter in-

MINERAL COMPOSITION OF THE IGNEOUS ROCKS

Acid	*Sub-acid*	*Sub-basic*	*Basic*	*Ultrabasic*
QUARTZ and ORTHOCLASE dominant	ORTHOCLASE dominant	Na-Ca PLAGIOCLASE and HORNBLENDE dominant	Ca-Na PLAGIOCLASE and AUGITE dominant	OLIVINE and AUGITE dominant
Little plagioclase Mica (biotite ± muscovite) Sometimes hornblende or augite	Some plagioclase Hornblende Sometimes quartz, biotite or augite	Little orthoclase Sometimes quartz, biotite or augite	Often some olivine or hornblende Sometimes a little quartz	No felspar or very little
PLUTONIC ROCKS GRANITE G=2.7	SYENITE G=2.75	DIORITE G=2.85	GABBRO G=2.9	PERIDOTITE G=3.0 to 3.3
MINOR INTRUSIONS Microgranite Quartz-porphyry	Orthoclase-porphyry	Porphyrite	Dolerite	
VOLCANIC ROCKS RHYOLITE Pumice OBSIDIAN G=2.4 ←	TRACHYTE Phonolite (with nepheline, etc.) volcanic	ANDESITE glass →	BASALT Tachylyte (rare) G=2.7	

cludes the mafic minerals, silicates of *magnesia* and iron (*Fe*), of which the chief are the micas, hornblende and other amphiboles, augite and other pyroxenes, and olivine. With the exception of quartz they all form mixed crystals of variable composition. This is especially true of the plagioclase fel-

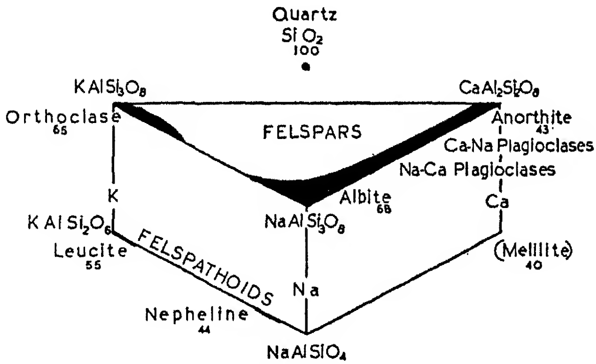

FIG. 5. The Chief Felsic Minerals. The figures represent the silica percentage.

CHEMICAL COMPOSITION OF SOME PLUTONIC IGNEOUS ROCKS

	Granite, Dartmoor	*Syenite, Plauen, Dresden*	*Diorite, Arran*	*Olivine-Gabbro, Skye*	*Peridotite, Loch Garabal, Argyll*
SiO_2	75.09	62.49	53.67	46.39	38.6
TiO_2	0.25	0.85	1.28	0.26	—
Al_2O_3	13.46	16.49	15.47	26.34	3.7
Fe_2O_3	0.74	2.36	3.24	2.02	7.6
FeO	1.05	2.04	7.25	3.15	7.8
MgO	0.74	1.87	4.90	4.82	27.7
CaO	0.66	4.23	8.28	15.29	7.7
K_2O	3.78	4.65	0.80	0.20	0.2
Na_2O	3.10	4.38	2.77	1.63	—
H_2O	0.91	0.60	1.96	0.58	6.4
P_2O_5, etc.	0.35	0.47	0.64	0.14	—
	100.13	100.43	100.26	100.82	99.7

spars, a series in which the end members, albite and anorthite, can mix in all proportions. The felspathoids are like the alkali felspars but have less silica. The composition and crystalline system of the chief minerals of the igneous rocks

are tabulated below; fuller details may be found in Rutley and Read's "Mineralogy" and Smith's "Minerals and the Microscope."

FELSIC MINERALS

		Silica %
Quartz. SiO_2. Trigonal.		100
Monoclinic felspars:		
Orthoclase. $KAlSi_3O_8$.		65
Triclinic felspars:		
Microcline. $KAlSi_3O_8$.		65
Soda-lime plagioclases. Mixtures of albite, $NaAlSi_3O_8$, with smaller proportions of anorthite,	Albite	68
	Oligoclase	
	Andesine	
Lime-soda plagioclases. Mixtures of anorthite, $CaAl_2Si_2O_8$, with smaller proportions of albite.	Labradorite	
	Bytownite	
	Anorthite	43
Felspathoids:		
Leucite, $KAl(SiO_3)_2$. Pseudo-cubic.		55
Nepheline. $K_2Na_6Al_8Si_9O_{34}$. Hexagonal.		44
Melilite. $(Ca,Fe,Mg)_{12}Al_4Si_9O_{36}$. Tetragonal.		40

MAFIC MINERALS

Muscovite (white mica). Silicate of Al, K, etc. Monoclinic.
Biotite (dark mica). Silicate of Al, Fe, Mg, etc. Monoclinic.
Hornblende. Silicate of Al, Fe, Mg, Ca, etc. Monoclinic.
Augite. Silicate of Ca, Mg, Fe, Al, etc. Monoclinic.
Olivine. $(Mg,Fe)_2SiO_4$. Orthorhombic.

Besides the essential minerals, felsic and mafic, there are accessory minerals which usually occur in very small proportions and the presence of which is not essential to the classification of the rock in which they may occur.

ACCESSORY MINERALS

Magnetite	Fe_3O_4	Cubic
Ilmenite	$FeTiO_3$	Hexagonal
Pyrite	FeS_2	Cubic
Pyrrhotite	Fe_7S_8	Hexagonal
Zircon	$ZrSiO_4$	Tetragonal
Apatite	$3Ca_3P_2O_8+Ca(F,Cl)_2$	Hexagonal
Sphene	$CaSiTiO_5$	Monoclinic

When the early-formed minerals have crystallised out of a magma, under plutonic conditions, the liquid residue is enriched in the volatile fluxes and the later minerals, such as alkali-felspar and quartz. If this residual juice is squeezed

out it may form veins cutting the granite and the surrounding rocks. This gives rise to the veins of aplite (quartz and felspar) and pegmatite, a coarsely crystalline rock. The residual liquor may be rich in such elements as boron, fluorine and lithium; it can then attack the felspars already formed and replace them by minerals containing those elements, such as tourmaline, topaz, fluorspar and lithia mica. This process is known as pneumatolysis. The conversion of felspar into kaolin is another function of magmatic liquors.

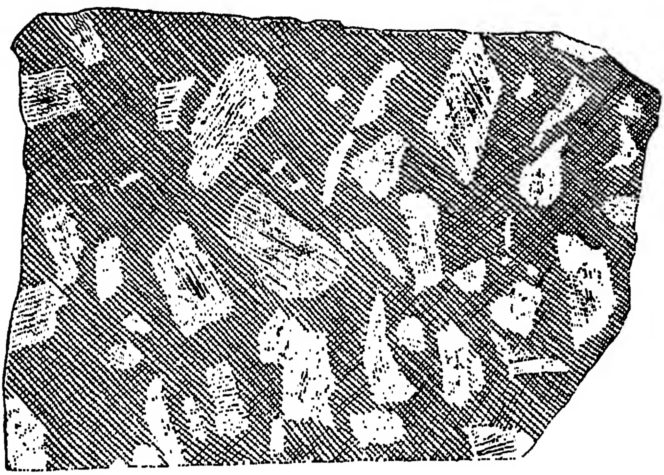

FIG. 6. Porphyry.

PNEUMATOLYTIC MINERALS

Fluorspar. CaF_2. Cubic.
Tourmaline. Boro-silicate of Al, Fe, Mg, etc. Trigonal.
Topaz. Silicate of Al with F. Orthorhombic.
Lithia mica. Silicate of Al and K with Li and F. Monoclinic.

British examples of granite include four masses in Cornwall and Dartmoor in Devon. Their felspars are rather long and white. The granite of Shap, in Westmorland, has large tabular felspars of a pink or brown colour. Aberdeen and Peterhead also supply good granites. The Mourne Mountains granite has numerous drusy cavities with well-shaped crystals.

The elvan dykes of Cornwall give good examples of quartz-porphyry, and rhyolites occur in the Lake District and North Wales. For fresh glassy rocks we must turn to recent volcanic areas, since glass is unstable and becomes devitrified; and the best obsidians are found in such places as the Lipari Isles, Mexico, and the Yellowstone Park.

Syenites are not common rocks. A well-known soda-syenite from Larvik, near Oslo, may be seen in many shop-fronts; it has a conspicuous play of colours in its felspars.

Gabbros occur in the Cuillin Hills of Skye, at St. David's Head, and the Lizard. Dolerites are quarried for road metal in many places. One intrusion of dolerite is the Whin Sill which stretches from the Northumberland coast to the Eden

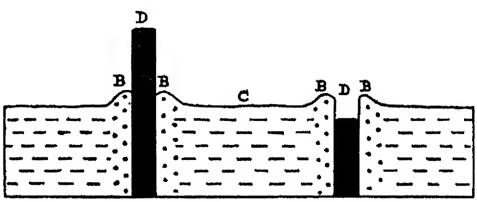

FIG. 7. Two Dykes, showing differential erosion.
C—Country Rock. D—Dyke.
B—Baked Contact.

valley and forms the fine crags which carry Hadrian's Wall. Basalts are very common rocks, and the columnar jointing, due to contraction on cooling, is well seen in the basalt of the Giants' Causeway and Staffa. The olivine of the ultrabasic rocks readily alters into serpentine, and serpentines occur in the Lizard, Anglesey (Holyhead), Banffshire (Portsoy), and the Shetlands. The ultra-basic rocks are the chief source of chromite, asbestos (chrysotile), nickel, platinum and diamond, while from granitic magmas we obtain tin, tungsten, mica and kaolin.

The forms taken by intrusive rocks (the volcanic rocks are considered in Chapter VII) include dykes, sills, laccolites, phacolites, necks, stocks and batholites. Dykes and sills are of considerable extent in two dimensions, while the thickness is relatively small. Dykes cut the bedding planes of the

country rocks (*i.e.*, the rocks into which they were intruded), while sills follow the bedding planes and are said to conform to them. Where the country rocks are but little inclined from the horizontal, dykes tend to be nearly vertical and to run across country in straight lines. They may resist weathering and stand up as walls or project like stone jetties from the

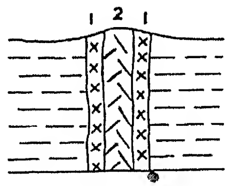

FIG. 8. A Composite Dyke.
2 is a later intrusion than 1.

coast. But others are more easily eroded than the country rocks and weather out as trenches. Some dykes have communicated with intrusive sheets or sills, and some with surface flows of lava (fissure eruptions). Some have been filled

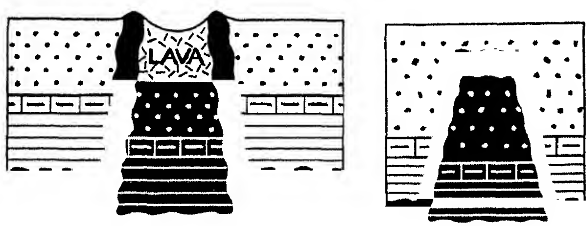

FIG. 9. Ring Dykes.

once and then cooled, while others have acted as conduits for continued upwellings of magma. Some have partially cooled and then been intruded by magma of a different composition, forming composite dykes. In multiple dykes the successive intrusions have approximately the same composition. The columns due to contraction on cooling run at right angles to the walls of the dyke, which are the cooling surfaces.

In many places dykes run in swarms with a common direction, like the N.W.-S.E. dykes in the Western Isles of Scotland. In Mull 375 dykes are crossed in a distance of 12½ miles of coast, and their aggregate thickness is about half a mile, which indicates a considerable stretching of the area at the time of intrusion.

While most dykes run in straight lines, ring dykes and cone sheets occupy arcuate, circular or oval fractures. The block of country within a ring dyke appears to have subsided, and the magma has been forced up around it. If the fracture reached the surface it formed a volcanic ring, filling the sunken area with lava. This is a cauldron subsi-

FIG. 10. Cone Sheets.

dence, examples of which have been described in Glen Coe and Mull. Other ring dykes may have fed boss-like intrusions. Cone sheets dip inward at an agle of some 45° and the country rock within them has presumably been lifted. They are very numerous about certain centres in Mull and Ardnamurchan, where they are separated by thin screens of older rock.

Sills occur especially in shales and thin-bedded limestones or sandstones, where the bedding planes are planes of weakness. The Whin Sill already mentioned follows the bedding planes of the Carboniferous Limestone, but not always the same plane. It sometimes transgresses from one horizon to another, breaking across the bedding along planes of least resistance. This ability to change its horizon is the chief distinction between an intrusive sill and a contemporaneous lava flow. Other diagnostic features are that a sill may bake the

beds above and below, contain fragments of both overlying and underlying beds, and show equal chilling effects at its upper and lower margins. A lava, on the other hand, cannot bake the overlying bed or contain fragments of it, but pieces of the lava may be included in the overlying bed.

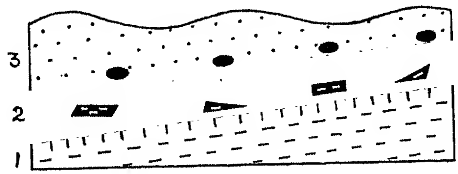

FIG. 11. Section through a Lava Flow.

Intrusive sheets often form striking features of dip-slope and escarpment; and a series of them gives a steplike appearance, whence the old name of trap rocks for the minor intrusions (from a Swedish word meaning a staircase).

Two other types of intrusion conformable to the bedding are laccolites and phacolites; but whereas sills lie for the most part between parallel planes, only tapering at the ends, these are lenticular bodies. The laccolites (=cistern rocks) described

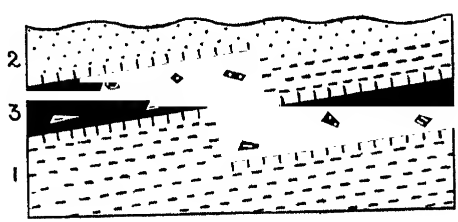

FIG. 12. Section through an Intrusive Sill.

by Gilbert in the Henry Mountains of Utah have highly convex tops and apparently plane bases, with hypothetic feeders. It was assumed that the pressure of the magma forced up the overlying beds into a dome; but unless these arched beds were badly fractured, in which case the magma would fill the cracks, it is hard to see how they can have fitted the undisturbed base. It may be that the base is really concave and

that the curvature is not the effect of the intrusion but its cause. In that case laccolites are indistinguishable from phacolites (=lentil rocks), which occupy the crests or troughs of folded strata, where the pressure is less than in the straight limbs between. Magma is forced into these low-pressure re-

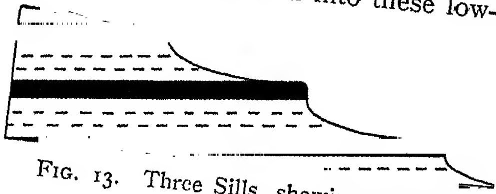

FIG. 13. Three Sills, showing step-like Outcrops.

gions if it can reach them. Corndon Hill in Shropshire is a phacolite of which the top and parts of the base have been exposed by denudation. Some writers distinguish intrusions in downfolds or synclines under the name of lopolites (=basin rocks), especially those of very large size, as at Sudbury, Ontario.

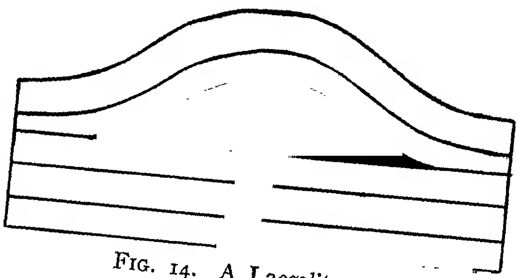

FIG. 14. A Laccolite.

Plugs or cores are roughly cylindrical intrusions. Some have acted as feeders to volcanoes and are then known as volcanic necks.

Stocks are irregular masses, cutting across the bedding planes. Offshoots more or less circular in section form bosses or cupolas. Batholites (=deep rocks) are huge masses, often some thousands of square miles in extent and of unknown depth. They occur among the oldest rocks, associated with gneisses and schists, as in Scandinavia and Canada, but later examples are known.

Igneous intrusions may be classified according to their relations with the country rock thus:—

Concordant	*Discordant*
Sills	Dykes
Laccolites	Plugs
Phacolites	Stocks
Lopolites	Bosses
	Batholites

Some writers prefer the clumsy terms laccoliths, phacoliths, etc., reserving the termination -ite for names of minerals and rocks.

Many plutonic masses are made up of two or more successive intrusions which differ in texture or in composition. A

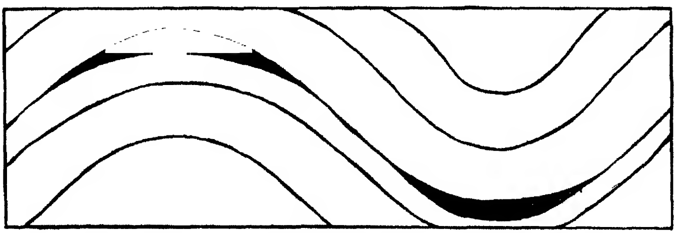

FIG. 15. Phacolite and Lopolite.

single intrusion too may be coarse-grained in the interior and very much finer at the margins, where it was chilled by the country rocks. In some cases the denser early-formed crystals, such as magnetite and olivine, have gravitated toward the base of an intrusion, leaving the upper part richer in light minerals such as felspar; and a single intrusion may be granitic in one part, dioritic in another.

It is hard to say what has become of the rocks displaced by the great batholithic masses. It has been suggested that the magma forced its way up, detaching blocks of roof rock which sank into it and were slowly melted and mingled with the magma. Such xenoliths (=stranger-rocks) are often seen near the margin of an intrusion. But most sedimentary rocks are less dense than granite and would not sink. They may have been forced down by crust movements; but some intrusions have been penetrated for a mile or more without reach-

ing any base. Another possibility is that solutions under high pressure may have penetrated upward, bringing with them those elements necessary to give sedimentary rocks the composition of igneous rocks, and that the granitisation of sediments may be an important and widespread process.

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CHAPTER V

SEDIMENTARY ROCKS

THE sedimentary rocks are very varied in composition and mode of origin, but they are all derived directly or indirectly from older rocks and have been deposited in water or on the land. Some are clearly fragmental, like the sandstones; others have been precipitated from solution by organic or chemical agents; others again result from the removal of material by weathering. High pressures or temperatures are not involved in their formation.

The popular association of hardness with rocks has no scientific support, for gravel, sand and clay are rocks as well as marble and granite. The sedimentary rocks include the following groups:—

1. *Pyroclastic rocks.*
   Volcanic tuffs, ashes and agglomerates.
2. *Clastic or detrital rocks.*

Unconsolidated	*Consolidated*
Boulder and scree deposits. Pebble beds and gravels.	Conglomerates, breccias.
Sands.	Sandstones, grits.
Silts. Muds and clays.	Shales, mudstones.

   (Some limestones are also in part clastic.)
3. *Rocks of organic origin.*
   Limestone (*e.g.*, shelly or coral limestone). Diatomite.
   Chert (*e.g.*, spicular or radiolarian chert). Peat and coal.
4. *Rocks of chemical origin.*
   Limestone (travertine, oolite, etc.). Gypsum.
   Siliceous sinter. Ironstone.
   Chert. Concretions.
   Rock salt.
5. *Weathering residues.*
   Clay-with-flints. Laterite. Soils.

Other terms used are rudaceous (=rubbly) for coarse deposits such as gravel, arenaceous for sands, argillaceous or pelitic for clays, calcareous for limestones, phosphatic, carbonaceous, siliceous, saline, etc. These are based on composition, not on origin.

The pyroclastic rocks form a link between the igneous and the sedimentary. The material is of volcanic origin but it has been blown to pieces by the explosive escape of steam and the fragments have fallen back on to the volcanic cone or neighbouring land or water, where they may be interbedded with normal sediments. The compacted rocks are known as tuffs; but the term ash is used for fine-grained deposits, and volcanic agglomerate for those containing coarse fragments. (See also Chapter VII.)

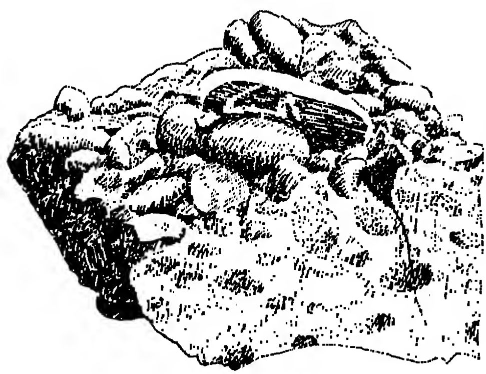

FIG. 16. Conglomerate.

The coarser detrital rocks may have accumulated almost *in situ,* like the scree or talus of frost-shattered fragments beneath a precipice; but in some cases big blocks have been transported by ice, as in moraines. Angular fragments in faults and veins, when consolidated, may also form breccias (=rubble of a broken wall, breach); and where fragments and cement are of different colours these breccias are often attractive stones when polished. Many brecciated marbles belong to this group. Pebble beds and gravels differ in the degree of rounding of the stones. Hard material like flint can only be rounded into pebbles by long-continued wave action, while river-transport does no more than round the edges, so that pebble beds are generally marine and gravels fluviatile; but a soft limestone may be rounded even by river action. Conglomerates are pebble beds consolidated with a calcareous,

siliceous or ferruginous cement, while in breccias the fragments are angular or subangular.

CHEMICAL COMPOSITION OF SOME SEDIMENTARY ROCKS

	Arenaceous, Lower Greensand	*Argillaceous, Gault Clay*	*Calcareous, Upper Chalk*
SiO_2	99.58	46.43	1.1
Al_2O_3	0.27	18.81	0.4
Fe_2O_3	0.03	9.97	—
CaO	0.22	6.78	55.1
MgO	—	0.99	0.1
K_2O, Na_2O	—	0.12	—
H_2O	—	10.48	—
CO_2	0.13	6.09	43.3
SO_3, P_2O_5	—	0.30	—
	100.23	99.97	100.0

FIG. 17. Breccia.

The Hertfordshire puddingstone is a good example of a conglomerate. Originally composed of flint pebbles and quartz sand, it now has a siliceous cement which gives the whole rock a flinty hardness. The Rand banket is a conglomerate rich in gold. Gem gravels in Ceylon, Burma, etc., are washed for sapphires, rubies and other gemstones. Gravels

are used for roads and paths, and when washed they make good aggregate for concrete.

Many different schemes have been adopted for defining the limits of the various grades in fragmental deposits. Crook proposed a convenient decimal system, in which the sand grade included all grains between 1 and 0.1 mm. in diameter; but grains both larger and smaller than these limits are commonly considered sand. Atterberg's system was recommended by an international congress, and his limits and Crook's are shown below :—

	Crook	*Atterberg*	
	Large stones and boulders	Blocks	
			200 mm.
		Cobbles	
			20 mm.
10 mm.		Pebbles	
	Gravel		
			2 mm.
1 mm.		Coarse sand	
	Sand		
			0.2 mm.
0.1 mm		Fine sand	
	Silt		
			0.02 mm.
0.01 mm.		Silt	
			0.002 mm.
	Mud	Clay	

Most sands consist mainly of quartz grains, but some shore sands and dune sands are made up of shell fragments with subordinate mineral grains. Coral sands are even more highly calcareous. In some places wave action concentrates the heavier mineral grains near high-water mark and forms black sands, rich in ilmenite or magnetite. Monazite sands are similar natural concentrates. Some river sands yield gold, platinum or tinstone. Glass sands should be almost pure quartz, free from iron and alumina.

Wave action has little power to round sand grains, and it is generally only wind-borne sands that are well rounded. Round grains serve therefore to indicate that desert conditions prevailed when they were deposited. Such millet-seed sands occur in the Permian and Triassic rocks of England.

Sands are normally white, but a very little iron may stain them yellow or red. In some cases the mineral glauconite gives a distinctly green colour. Manganese oxide or carbonaceous matter makes some sands grey or black.

Sandstones may be calcareous, ferruginous or siliceous,

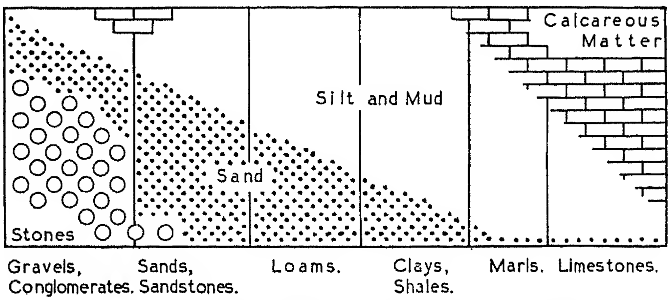

FIG. 18. Composition of Sedimentary Rocks.

according to the nature of the cement. Quartzites and ganisters are high-silica rocks. Arkoses contain much felspar. Grits are usually coarse-grained sandstones, but the term has been used in many different senses. Greywackes are grits formed of rock particles, common among the Palæozoic rocks. Flagstones have a fissility which is often due to flakes of mica lying in the bedding planes.

Silt, mud and clay are usually deposited in water, but boulder clays are formed by glaciers and ice-sheets, and loess is a wind-blown silt which covers wide areas in China, Europe and North America. Where a river enters a lake the mud suspended in the river water is thrown down in the still water of the lake. Estuaries tend to be muddy because the salt water makes the tiny particles of mud flocculate into larger aggregates, which sink more rapidly. But currents carry much of the mud far from the shore, and large areas of the sea floor are covered with mud. Sandy clays are called

FIG. 19. Frosterley Marble, with Corals.

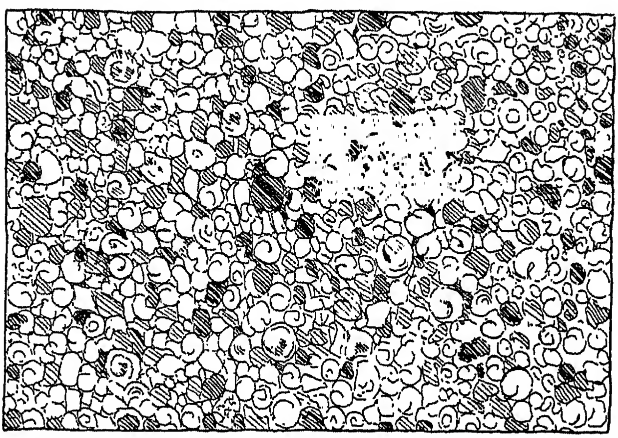

FIG. 20. Purbeck Marble, with Freshwater Shells.

loam and calcareous clays marl. Indurated clays are called mudstone if there is no lamination, or shale if they are laminated along the bedding planes.

The shell and coral sands already alluded to would form limestones on consolidation, and so would accumulations of

fragments of older limestones, such as beach deposits below limestone cliffs. Some Liassic limestones in Glamorgan are so formed from debris of Carboniferous Limestone. Most limestones, however, are accumulations of calcareous organic remains, whether corals, crinoids, mollusca, brachiopods, foraminifera or calcareous algæ. Mingled with these organisms there may be chemical precipitates, ooliths or calcitic mud; and there is often much impurity, giving sandy and argillaceous limestones. The limestone known as Frosterley marble, from Weardale, shows many large corals,

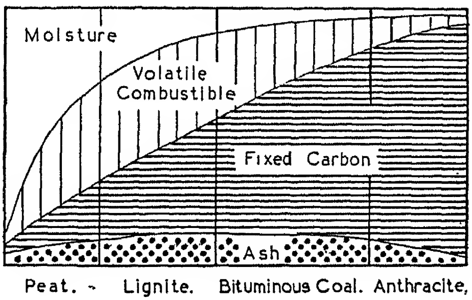

FIG. 21. Composition of Coals.

while the Purbeck marble is full of shells of the fresh-water snail *Viviparus* (*Paludina*).

Beds of chert are often due to organisms that secrete silica, such as sponges, radiolaria and diatoms. But other cherts are chemical alterations of limestones.

Diatomite is a very light rock composed of the thin-walled siliceous frustules of diatoms, which are unicellular plants. After calcining it is used under the name of tripoli or kieselguhr for polishing, filtration, absorbing chemicals, heat insulation, and other purposes.

Peat and coal are carbonaceous deposits composed of vegetable matter in different stages of alteration. The changes involve loss of moisture and volatile combustible matter and increase in fixed carbon.

Chemical action may give rise to rocks of very varied composition. The stalagmite that covers the floor of limestone

caverns and the calcareous tufa and travertine thrown down by petrifying springs are due to solution and precipitation of calcium carbonate. Ooliths are formed in warm shallow waters saturated with $CaCO_3$, as on the shores of the Bahamas and the Great Salt Lake of Utah, where sand grains or shell fragments rolled about by the waves acquire concentric coatings of calcite. When consolidated into the rock known as oolite they bear some resemblance to the roe of a fish, whence the name is derived (=egg stone). Larger accretions form pisolite (=pea stone), like the pea grit of the Cotteswolds. The pisolite formed by the Carlsbad hot spring consists of aragonite.

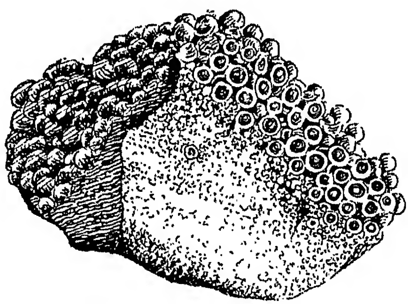

FIG. 22. Pisolite.

Sometimes the precipitate forms a calcitic mud. Such a mud binds the oolite grains and shell fragments in many oolites, as in the Portland Stone and Bath Stone. It forms the bulk of the Chalk, which probably originated in a warm and shallow sea. Chalk contains a few foraminifera, including *Globigerina*, but it is certainly not analogous to the *Globigerina* ooze of the ocean deeps, as was formerly supposed.

Magnesium salts in water may replace part of the calcium in limestones by magnesium, giving a mixture of calcite, $CaCO_3$, and dolomite, $CaMg(CO_3)_2$. The Permian Magnesian Limestone of N.E. England is an example of this, and parts of the Carboniferous Limestone are dolomitic.

Hot springs and geysers bring up silica in solution, and

as the water cools this is deposited as siliceous sinter. It may build mounds about the vents.

The chert associated with pillow lavas (p. 46) is also probably derived from magmatic water. Other cherts are replacements of limestone by silica dissolved in cold water, in which its solubility is slight.

When bodies of sea water evaporate in arid climates the slightly soluble sulphate of lime is thrown down first, usually as gypsum, $CaSO_4.2H_2O$, but in warm water as anhydrite,

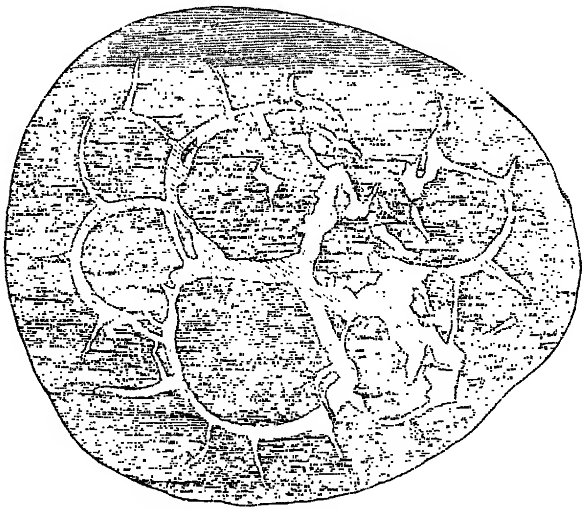

FIG. 23. Septarian Concretion, in section.

$CaSO_4$. It is followed by rock-salt, NaCl, and this association is seen in our Permian and Triassic salt deposits. The less abundant but highly soluble potassium salts are only rarely precipitated, as at Stassfurt in Germany. Borings have revealed potassium salts in the Permian of Yorkshire.

Gypsum may also be formed by the oxidation of pyrite, FeS_2, disseminated in clays and the reaction of the SO_3 so produced on the calcitic matter of fossils. Fine crystals, known as selenite, are formed in this way in many clays.

Hydrated ferric oxide is precipitated in some swamps as bog iron ore. It often impregnates leaves and mosses and may be in part due to bacterial agency. Other iron ores, like

the Cumberland hæmatite, are replacements of limestone; but the ferruginous pisolites and oolites are not in all cases secondary after limestones as was formerly believed.

Concretions are of many kinds—calcareous, siliceous, ferruginous, phosphatic. In general they arise from the solution of material sparsely disseminated through a sediment and its concentration in nodules. Thus the flint nodules in the Chalk are formed of silica derived from sponge spicules, and remains of sponges are often enclosed in them. Some nodular cherts are very similar to flint in appearance and origin. Calcareous concretions are common in clays. Some are septarian, as in the London Clay, the mass of cemented clay being traversed by septa or walls of clear calcite which are widest toward the centre and taper toward the outer part of the septarium. Some clay-ironstone nodules in the Coal Measures are also septarian, but with siderite, $FeCO_3$, in place of calcite, $CaCO_3$.

Nodules lying in one bedding plane may grow till they merge into one another, forming a continuous bed. Some of the Lower Lias limestones have been formed in this way, and so have some tabular flints in the Chalk.

Nodules of pyrite, FeS_2, with radiating structure, occur in the Chalk, the Gault and other clays. Concretionary limonite, $H_6Fe_4O_9$, in sands takes on many forms, cementing sand grains locally into iron-sandstone or carstone. Some of these are cylindrical bodies, others are hollow spheres known as boxstones and Adam's snuff boxes. Phosphatic nodules in the Gault and Chalk seem to mark pauses in the deposition of the sediment.

Among weathering residues the most widespread are the soils. In quarries and cuttings the gradual passage from solid rock to soil may often be seen. A large part of the Chalk uplands is covered by a few feet of red-brown clay with unworn flints. This clay-with-flints represents the insoluble residue of chalk that has been dissolved by rain, though there is some admixture with Eocene sands and clays.

In hot moist climates silicates are more completely broken up than in temperate lands, the silica itself being removed

in solution. What is left is mainly hydrated alumina and ferric oxide (bauxite and limonite). If little or no iron is present the bauxite forms a valuable ore of aluminium; but more frequently a brick-red mass of laterite is the result of weathering in moist tropical climates.

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CHAPTER VI

METAMORPHIC ROCKS

METAMORPHIC rocks are those that have developed new minerals or new structures, or both, as a result of heat and pressure, so that they differ markedly from the original rocks. Metamorphism (change of form) may or may not be accompanied by metasomatism (change of body), whereby

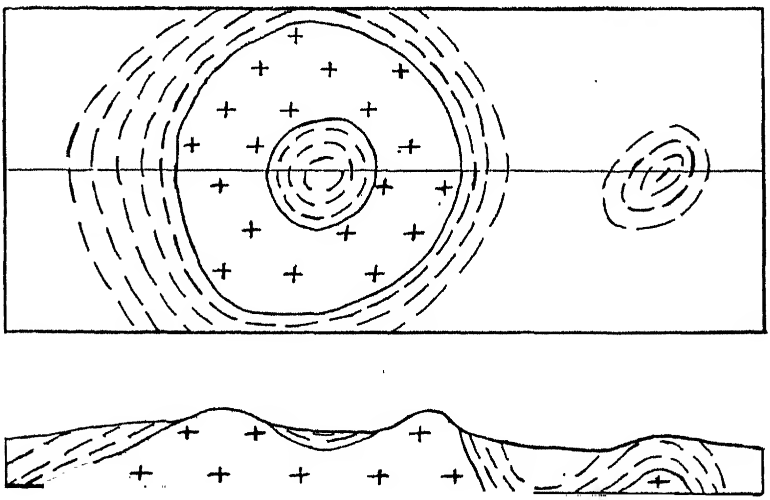

FIG. 24. Metamorphic Aureole.
In plan and section. Crosses, granite. Dashes, altered rock.

the bulk composition of the rock is altered. It does not include changes at low temperature and pressure, such as cementation, recrystallisation and weathering, or at temperatures high enough to fuse the rocks.

It is customary to distinguish between thermal metamorphism, in which the effects of heat are dominant, and dynamic metamorphism, where crust movements have induced crushing and shearing. But both factors have oper-

ated, to a greater or less extent, in most if not all metamorphic rocks.

Another distinction is between contact metamorphism, which affects a narrow zone or aureole near an igneous contact, and regional metamorphism, where the rocks over wide areas were formerly buried deep beneath the surface, where both pressure and temperature are high.

The minerals commonly developed in metamorphic rocks include quartz, felspars, micas, chlorite, garnet, andalusite, sillimanite, kyanite, hornblende, tremolite and calcite. Some

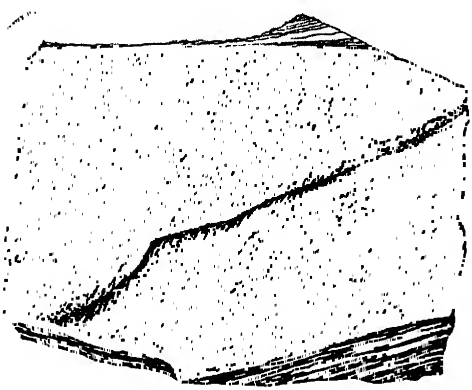

FIG. 25. Schist.

of these, like garnet, have relatively high densities due to the close packing of atoms under high pressure. Of the aluminium silicates (Al_2SiO_5), andalusite and chiastolite occur in rocks of low-grade metamorphism, sillimanite is intermediate, and kyanite is found where the pressure has been highest; this is also the order of increasing density.

The pressure is not uniform, as in fluids, but greatest in one direction (directed pressure). Platy minerals like mica and chlorite tend to set themselves, and to grow, in planes at right angles to the direction of greatest pressure. They often form thin bands alternating with quartz, felspar, etc.; and this causes a foliated structure best seen in the schists, which split readily into parallel-sided plates. In gneisses the foliation is less perfect and the crystals are usually coarser,

but the platy minerals often wrap themselves round lenticles of quartz giving an augen (or eye) structure. The composition may be indicated by prefixes, *e.g.*, chlorite-schist, garnet-mica-schist, diorite-gneiss.

Where there is no such parallelism, minute crystals grow in all directions and interlock, giving a tougher rock called hornfels.

Orthogneisses are altered igneous rocks and paragneisses are altered sediments. Where a granitic magma has been

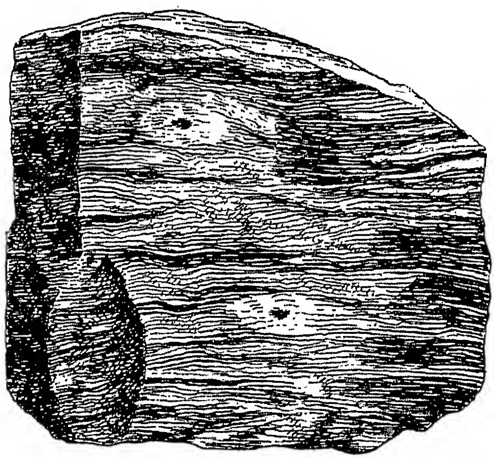

FIG. 26. Augen Gneiss.

injected between the foliation planes of a schist a compound gneiss or migmatite results. The magmatic fluids may permeate the schist and gradually make it over into a granitic rock; and it is possible that many granitic masses may have originated in such a manner.

Dynamic metamorphism at fairly low temperature gives rise to intense crushing and shearing. Minerals become granulated, often with large grains set in fine comminuted fragments (mortar structure). Mylonite (=milled rock) is a streaky chertlike rock sometimes formed during overthrusting, in which the minerals have been ground fine as though

beneath a millstone. At higher temperatures these effects become less noticeable.

A pure quartzose sand, by the growth and interlocking of its quartz grains, recrystallises as a metamorphic quartzite, the effects of strain being visible under the microscope. Felspathic and argillaceous impurities give felspar and mica.

It is the fine-grained heterogeneous sediments that give the greatest variety of metamorphic rocks. Slates are argillaceous rocks, or in some cases volcanic ashes, that have developed slaty cleavage under low-grade dynamic metamorphism. The cleavage is independent of the bedding, whereas

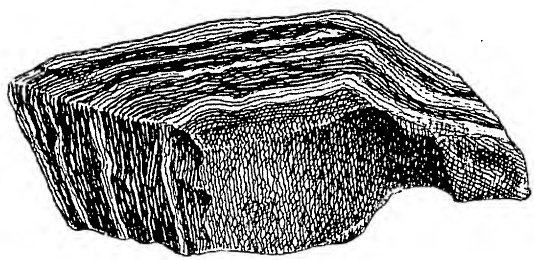

FIG. 27. Contorted Gneiss.

in shales the laminations are in the bedding planes. Fossils are therefore seldom preserved in slates except in places where the cleavage planes happen to coincide with the bedding, and even then they are distorted by the shearing that has taken place. Slightly greater metamorphism produces spotted slates, and the spots may pass into definite crystals of chiastolite, mica, or cordierite. Phyllites are micaceous slates or fine-grained schists. Organic matter is reduced to graphite. With higher-grade metamorphism a great variety of schists may be produced.

The calcareous rocks too yield many types of metamorphic rock. A pure limestone may recrystallise into a white statuary marble like that of Carrara. With silica alone the lime silicate wollastonite ($CaSiO_3$) is formed. Magnesian limestones may give forsterite (a mineral of the olivine group, Mg_2SiO_4), and

this readily alters to serpentine. The serpentinous marbles are called ophicalcites and are often beautiful rocks when polished, like the stones known as Irish Green from Connemara and Verde Antico from Greece.

Alumina in impure magnesian limestones may form spinel ($MgAl_2O_4$) or corundum (Al_2O_3). Indeed most of the corundum gems, rubies and sapphires, have originated in marbles, though they are obtained from gravels in which they have been concentrated by streams.

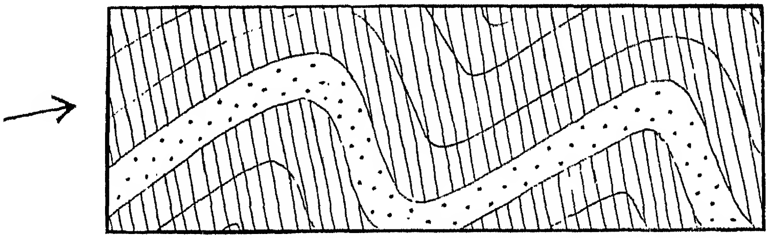

FIG. 28. Slaty Cleavage.

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CHAPTER VII

VOLCANOES

WHEN a molten magma reaches the surface of the earth it commonly forms a volcano. Having pierced a cylindrical hole through the country rocks it may well up gently and spread out in successive lava flows to build up a shield or cone of very low angle, as in Hawaii. A more viscous lava builds a steeper cone or dome. Frequently the escaping steam blows the magma to fragments which are shot up into the air and fall back to form an ash cone, with a slope depending on the

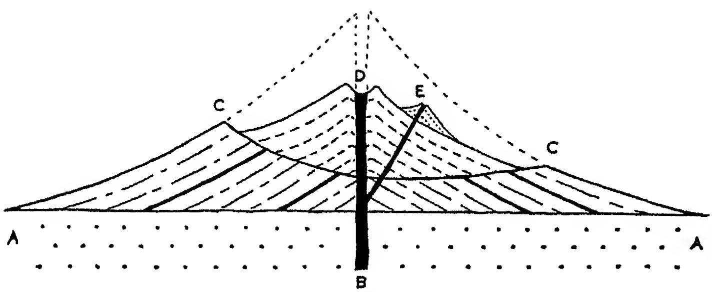

FIG. 29. Volcano in Section.
A—Country Rock. B—Neck. C—Old Crater Rim. D—Crater.
E—Parasitic Cone.

angle of rest of the fragments. Composite cones are often formed, partly ash and partly lava flows. Parasitic cones may rise on the flanks of an old volcano; and after long quiescence a paroxysmal explosion may blow away the greater part of the cone and build a new one within it, like Vesuvius within the shattered rim of Monte Somma.

In size volcanoes vary from 100 or 200 feet to giants like those of the Andes, which reach 20,000 or 23,000 feet above sea level. However, only about half of this is volcanic matter, which rests on a platform of older rocks; and these Andean volcanoes are far exceeded by those of Hawaii, which rise

from some 20,000 feet below sea level to nearly 14,000 feet above it and form a low cone or shield with a base of 130 by 160 miles. This is the greatest known bulk of lava associated with central volcanoes, but far greater volumes seem to have been poured out by fissure eruptions.

The popular conception of a volcano as a burning mountain is wrong. The heat derived from combustible gases (H, CH_4, etc.) is a very small part of the heat involved; and the appearance of smoke and flames is mainly due to the clouds of condensed steam and dust which at night reflect the glowing lava below. Such terms as ash, cinder and indeed igneous, have an unfortunate suggestion of combustion.

The magma consists of molten silicates, consolidating as lava, and volatile fluxes, most of which escape into the air. Of these H_2O is the most important, but there are also CO_2, HCl, and other gases. The acid magmas, with high silica content, are very viscous even at high temperatures, and especially so when they have lost their fluxes. The gases pent up within them at high pressure escape with difficulty, often with explosive violence, and there is much shattering and production of ash. Pumice may be formed, a glassy rock so full of tiny steam cavities that it will float on water. In scoria the cavities are larger. Steam cavities may become filled with secondary minerals, such as silica, calcite and the hydrated silicates known as zeolites: the rock is then an amygdaloid (=almond shape). The high viscosity of acid magmas hinders crystallisation and so there is much glass; indeed most volcanic glass is obsidian, of rhyolitic or trachytic composition (p. 14).

Basic magmas are far more fluid, although they commonly contain less of the volatile fluxes. Hence the gases escape easily and without violence, leaving large vesicles, and the atoms are free to come together and build crystals. There is a little residual glass between the crystals in some basalts, but the basic glass, tachylyte, occurs only rarely and in small quantity.

The crater of a volcano may be enlarged by the material of the cone slumping down into it, as in Hawaii, or by withdrawal of lava through a side orifice, or by an explosion.

These widened craters are known as calderas, after the Caldera of Palma in the Canary Islands.

Much of the steam emitted during an eruption is condensed and falls back as torrents of rain. Ash and water may form destructive mud-flows, like that which overwhelmed Herculaneum. Rain-erosion starts with the very formation of the volcano, and most ash cones show radial gullies or barrancos. Volcanic ash is easily eroded; lavas are more resistant and persist for some time as flat-topped hills, but eventually only the volcanic neck is left. This may form a steep hill or crag like the Rocher St. Michel in Velay. On both shores of the Firth of Forth one may trace the outlines of volcanic necks of Carboniferous age that have been reduced to sea level.

The type of eruption, whether violent or gentle, the products of eruption, solid, liquid and gaseous, and the form of the volcano, all depend on the explosive force; and this in turn is governed by the water content and the viscosity of the magma. Generally speaking, the more acid the magma the more violent is the eruption and the greater the production of fine volcanic ash. Five types of eruption have been distinguished.

1. *The Hawaiian type.* Here very fluid basaltic lava wells up gently, without any explosions and with no fragmental material. Successive flows build up a shield of very gentle slope. There are two great vents in Hawaii, Mauna Loa and Kilauea, and two dormant ones. In the active vents the lava rises slowly till it breaks out, sometimes spouting like molten metal; and it may flow fifty miles before solidifying. Sometimes it falls into the sea, producing clouds of steam and the ellipsoidal masses known as pillow lava. The lava streams have a solid crust while the interior is still liquid, and the liquid may drain away, leaving a lava tunnel. The crust may be fractured and blocky, when it is known by the native name of aa; elsewhere it is smooth and ropy and is called pahoehoe. Large bubbles of steam rise in the crater and burst, when the wind draws out the lava into threads like spun glass which collect on ledges of the crater wall. This is Pele's hair, Pele being a goddess supposed to live in the volcano.

While the lava floor in Mauna Loa stands at nearly 14,000 feet above sea level, it is only 4,000 feet in Kilauea. Each vent therefore must have its own independent lava reservoir; otherwise hydrostatic pressure would equalise the levels.

2. *The Strombolian type.* Stromboli is one of the Lipari Islands lying north of Sicily. The magma is fairly liquid, giving lava flows and also large fragments, but there is little fine ash, which requires greater explosive force. The cone is therefore a composite one; it is about 5,000 feet high, but half of it is below sea level. Puffs of steam are constantly rising from cracks in the crater floor or forming bubbles in the liquid lava which on bursting throw fragments hundreds of feet into the air, so building up the cone. At night the incandescent lava lights up the steam clouds and gives Stromboli its title of the lighthouse of the Mediterranean. It is this constant activity that prevents the vent getting choked and the pressure increasing for a more violent eruption.

Many of the fragments thrown up are of liquid lava which solidifies in the air. Their spin gives them an ellipsoidal form. The larger ones, down to the size of a walnut, are called volcanic bombs; those between walnut and pea size are lapilli (=little stones) and all smaller material is volcanic ash. Some bombs have a glazed and crackled surface: these are bread-crust bombs. Consolidated ash is called tuff—or volcanic breccia or agglomerate if it includes bombs, lapilli, or fragments of older lava or of the country rock.

3. *The Vulcanian type.* Vulcano is another of the Lipari Isles. The magma here is more viscous, constantly plugging up the vent. The effect of this is like tying up the safety-valve of a boiler; the steam pressure increases until it escapes with violent explosion and pulverisation of the magma. Steam and dust then rise in a cloud of typical cauliflower form. Lava flows are exceptional and small. Vesuvius conforms to the Strombolian type for years at a time; then there is a lull, followed by a Vulcanian eruption like that of A.D. 79, which blew away the southern half of the old cone, leaving Monte Somma as a relic. These violent explosions are sometimes described as of Plinian type.

4. *The Peléan Type.* Mont Pelée is in Martinique in the

West Indies, but similar eruptions occur in Japan and Java, associated with lavas that are andesites or quartz-andesites (dacites). These lavas are very viscous, so that they may be slowly protruded upward as an incandescent mass too viscous to flow. When once the vent has been cleared, the volcano boils over and a *nuée ardente,* or emulsion of white-hot gas and solid particles, rolls down the mountain side almost like a liquid. Such an incandescent cloud, on 8th May, 1902, covered the five miles from Mont Pelée to St. Pierre in about two minutes, destroying the city and killing 20,000 people. The Soufrière in the neighbouring island of St. Vincent erupted at the same time, but with less destruction. In neither case were any lava flows emitted, but fine volcanic ash accumulated to a depth of 50 or 60 feet.

Subsequently a column of lava was slowly pushed up from the crater of Mont Pelée as a glowing spine which reached a height of 1,500 feet by May, 1903, but it soon crumbled away. The domes of Auvergne are masses of trachytic lava which seem to have been squeezed out in a similar manner.

In 1912 a *nuée ardente* covered the Valley of Ten Thousand Smokes in Alaska with a "sand flow" of ash and lapilli rendered mobile by escaping gas. It was followed by a paroxysmal eruption of the neighbouring Mount Katmai, which had long been quiescent but which now in a series of terrific explosions emitted quantities of fine rhyolitic ash. Some of it fell at Vancouver, 1,300 miles away. The total volume of ash emitted in this double event has been estimated at six cubic miles.

5. *The Krakatoan type.* This represents the extreme of volcanic violence, and the eruption of Krakatoa on 27th August, 1883, is, mercifully, unique in human experience. A series of terrific explosions emptied the magma reservoir, and the cover collapsed, leaving a caldera four miles across and with 1,000 feet of water where the mountainous centre of the island had been. The sea was greatly disturbed, and waves more than 50 feet high swept over the shores of Java and Sumatra, drowning 36,000 inhabitants. Dust was shot up 20 miles high, causing a blackness as of night 100 miles

away; and some of it is said to have travelled round the world three times before it settled. Remarkably fine sunsets were seen in England as a result of this dust in the atmosphere.

Submarine eruptions may belong to any of these types. They have given rise to many groups of islands in the Pacific Ocean. But small islands, especially those formed of volcanic ash, are soon cut down by the waves, as was the case with Graham's Island which appeared in the Mediterranean in 1831.

Pillow lavas are often associated with submarine eruptions. They may have been poured out on, or just below, the soft muds of a sea floor. The steam evolved from the sea water may in some cases have floated the pillows for a time. The presence of secondary albite, even in basaltic lavas, is a common feature of pillow lavas; and the spaces between the pillows may become filled with silica or carbonates.

So far we have considered volcanoes of the central type, with roughly cylindrical vents. They are to-day the commonest and most spectacular. But in the past far greater volumes of lava have been emitted from long narrow cracks or fissures in the earth's crust. For example, the late Cretaceous Deccan traps cover about 200,000 square miles in India, and their thickness now, after much denudation, varies between 200 and 6,000 feet. The Columbia lavas cover a somewhat greater area west of the Rocky Mountains to a thickness of over 4,000 feet in places. The basalt plateaux of Antrim and the Western Isles of Scotland may in Eocene times have been continuous with those of Iceland, where the lavas are 5,000 feet thick.

It is in Iceland that fissure eruptions can best be studied to-day. One of the fissures, called *gja,* is 18 miles long and 600 feet deep, but only a few feet wide. The fissures seem to be independent of surface features, and may appear close to the top of a cliff; but they often show a parallelism among themselves. Some of them are capped by a string of little craters. In the eruption of 1783 at Laki in Southern Iceland an old fissure reopened for a length of 20 miles, and streams of basalt spread over the surrounding country. They flowed

down two valleys for 40 miles, and it is estimated that three cubic miles of basalt were brought up in that one eruption.

Mud volcanoes, as seen in Burma and the Caucasus, are not really volcanic phenomena, though some small examples elsewhere are connected with hot springs. The motive power is not steam but gas. A good example is Shugo in the Western Caucasus, which has a perfect crater ¾ mile across, filled with mud bleached white, and covered by little domes and cones. From some of these minor craters cold salt water wells up gently, while gas rises in others, sometimes noisily, hurling stones and mud 20 feet into the air. The gas is almost wholly methane, CH_4, and the "volcanoes" have periods of quiescence and violence. In both the Caucasus and Burma mud volcanoes seem to occur on fractured anticlines in which oil had collected; but the oil has escaped up the fracture planes leaving only gas and salt water, as in an exhausted oil field.

There are about 500 active volcanoes in the world to-day, and some thousands of dormant and recently extinct cones. They are distributed along two great belts. One of these is the "girdle of fire" around the Pacific, running up the Andes and through Central America, Mexico, the western United States and Canada to Alaska, and then through the Aleutian Islands, Japan and the Philippines. The other runs from Central America eastward through the West Indies, Azores, Cape Verde and Canary Islands, the Mediterranean, Asia Minor and the East Indies.

The British area has been the scene of volcanic activity many times in the past. There are excellent examples of pillow lavas in Anglesey and the Lleyn Peninsula. Shropshire has its Uriconian rhyolitic lavas and ashes, and there are tuffs and breccias in Charnwood Forest, near Leicester. All these are of Pre-Cambrian age. There was great volcanic activity in Ordovician times, giving rise to the Borrowdale Volcanic Series of andesitic and rhyolitic lavas and ashes in the Lake District and to similar rocks in North Wales and Shropshire. Devonian pillow lavas, basalts and ashes occur in Cornwall and Devon, and in Scotland vulcanicity lasted through Devonian and Carboniferous times. There are some

Permian lavas around Exeter, after which there was quiescence until the basalts of Antrim and the Western Isles of Scotland were poured out, largely by fissure eruptions, in Eocene times.

After all eruptions have ceased, the emission of gases, steam and hot water may continue for many centuries, marking the phase of waning vulcanicity. It is often termed the solfataric phase, although only those vents from which H_2S rises and deposits sulphur are solfataras. Fumarole (=smoker) is a more general term. It is only the hotter fumaroles that emit H_2S and HCl; they may occur in the

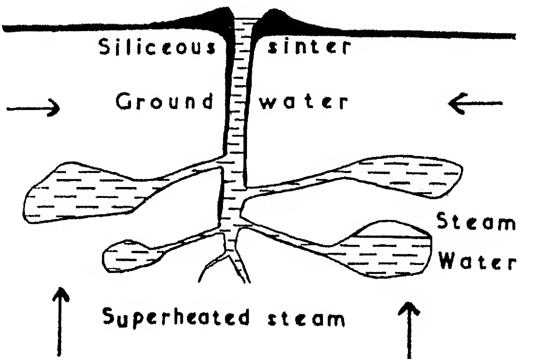

FIG. 30. Geyser in section.

central part of a volcanic region while CO_2 and steam rise from the cooler peripheral parts. The heavy gas CO_2 may collect in a hollow and form a "death gulch," suffocating small animals, although a man, horse or deer can traverse it safely. In the Grotto del Cane, near Naples, a small dog was used to demonstrate the asphyxiating properties of the gas that lies near the floor.

Hot springs consist wholly or in part of magmatic water, as is shown by their content of such elements as sulphur, arsenic and boron. But some may be surface water that has been heated by contact with lavas, as in the Yellowstone Park. Some will provide a warm bath; others will boil an

egg. The boiling springs may simmer gently, but some are in violent ebullition, approaching geysers in character. The escaping water remains clear, but if the loss by evaporation equals the inflow there is no overflow and the mud brought up accumulates in the hot spring basin. It may be white mud or tinted yellow, red, purple or black by oxides of iron and manganese, forming "paint pots." If the mud becomes very thick and viscous it may build up a mud volcano.

Geyser is an Icelandic word meaning "gusher," and geysers occur only in Iceland, the Yellowstone Park and New Zealand. They throw up columns of water at regular or irregular intervals, which may be a few minutes or several hours. They are generally surrounded by a wide basin lined with geyserite, or siliceous sinter, and some have built up mounds of geyserite around the vent, as in the Beehive Geyser in the Yellowstone Park. The water escaping from some geysers carries lime and has built up terraces of travertine.

Geyser action depends on a balance between cool water circulating in the rocks and superheated steam rising from the magma below. With no ground water we have a steam-vent; with too much, a hot spring. The great volume of water discharged by many geysers must require underground chambers, lava tunnels and the like, for its accumulation. After an eruption these fill fairly quickly from connected fissures and cavities, and the water is gradually heated by steam from below. The boiling point is raised by the pressure of the column of water in the tube. When the water in any chamber reaches the boiling point appropriate to the depth, steam begins to form and forces hot water into the geyser tube. Eventually steam forms there, too, rises, expands, and heaves some of the water out of the basin. With this relief of pressure large volumes of water flash into steam, and steam and water are ejected, sometimes 200 feet or more into the air.

In considering the causes of volcanic action we must remember that vulcanicity is only one phase of igneous action, which includes also the plutonic and minor intrusions. The magma does not come from any residual liquid core or zone within the earth's crust; the transmission of seismic waves

precludes that. Moreover, the difference in level of the lava in Mauna Loa and Kilauea, and the different compositions of the lavas of neighbouring volcanoes, show that there is no common reservoir. However, neighbouring volcanoes emit lava sufficiently similar to suggest consanguinity, derivation from a common stock; and they often erupt in sympathy. So we must picture each volcano as having its own private reservoir which has been filled and may be replenished from a larger and more deep-seated body of magma. These more permanent bodies are at a depth where the rocks are near the temperature of fusion, and where a small access of heat (or a small relief of pressure) will cause melting.

The generation of heat has been attributed to mechanical crushing of rock masses forced one over another. But this is a slow process, and the heat evolved would be dissipated without causing extensive fusion. Heat arising from the degradation of radioactive elements is more competent, and it is possible that relief of pressure at depths where the solid and liquid phases are in approximate equilibrium may be the cause of much fusion.

Changes of pressure due to crustal movement are certainly the cause of movements of magma, if not of its production. The linear arrangement of volcanoes along axes of folding is well seen, for example, in the Andes and the Caucasus. Fissure eruptions seem to be connected with upheaval or depression of great blocks of country and not with crumpling under tangential pressure.

Water plays a large part in many eruptions, but it is not the prime mover. And it is not water that has descended through the surface rocks till it has come in contact with rocks at high temperature. How far the concentration upward of magmatic water is effective in promoting fusion and in drilling an outlet to the surface is still uncertain.

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CHAPTER VIII

EARTHQUAKES

In an earthquake the earth quakes or trembles because it has received a shock. The shock is sometimes due to a violent volcanic outburst, as at Krakatoa in 1883; or the caving in of an underground cavern; or an explosion like that of the mines on Vimy Ridge in 1917. But all these give only slight and local effects. The great earthquakes are produced by movement of rock masses along fractures or faults.

The movement may affect 40 or 50 miles of rock, so that the energy released is considerable. The motion may be vertical, horizontal, or oblique. At San Francisco in 1906 fences that crossed the fault were broken and shifted up to 20 feet horizontally, but the vertical displacement was nowhere more than 2 or 3 feet. But frequently vertical movement is dominant, giving a fault scarp.

The actual movement of large masses of rock takes place slowly, with gradually increasing strain. This is relieved by a sudden snap and movement of rocks adjacent to the fracture, perhaps for a few feet. They may oscillate for a while before coming to rest; after which the same slow crustal movement continues until the breaking stress is again reached. A fault with a throw of hundreds of feet is the record of numbers of small displacements. It is this sudden snap and movement that originate the earthquake waves which carry the destructive effects far from the origin and may even affect instruments on the other side of the earth.

Thus the sinking or lateral shifting of a tract of country is not the effect of an earthquake but its cause. Buildings in the immediate neighbourhood of the fault may be damaged by this local movement, but more distant damage is due to the tremors set up by it and propagated outward through the earth. These seismic waves emerge as short rapid vibra-

tions rarely more than a few inches in amplitude. They are far from simple waves, and a particle affected by them describes a very complex path, up and down, to and fro, and sideways.

It was formerly thought that earthquakes were generated at a point or focus some miles below the surface. The point on the surface immediately above it was called the epicentre, and the position of the epicentre was found from closed curves (coseismal lines) drawn through points at which waves arrived at the same time. This led to discordant results; there seemed to be several epicentres in a line, and the line often proved to be a fault.

Several different scales have been devised for comparing the intensities of different earthquakes, or of the same earthquake at different distances from the epicentre. In the Rossi-Forel scale there are ten degrees, as under.

ROSSI-FOREL SCALE OF SEISMIC INTENSITIES.

1 and 2. Known mainly from records on special instruments (seismographs); but 1 may be noticed by an experienced observer and 2 by a few people at rest.
3. Generally felt by people at rest.
4. Felt by people in motion; doors and windows rattle.
5. Generally felt; disturbance of furniture.
6. Sleepers awakened; clocks stopped; chandeliers set swinging.
7. Movable objects overthrown; church bells rung; panic.
8. Chimneys overthrown; walls cracked.
9. Some buildings destroyed.
10. Widespread devastation.

On this scale most of the earthquakes felt in the British Isles are of intensities 3 or 4; but the Glasgow earthquake of 1910 reached intensity 5½, Inverness 1901 8, and Colchester 1884 8½.

The various phenomena connected with earthquakes may be described in connection with a few typical examples. The Lisbon earthquake of 1755, November 1st, consisted of three main shocks, at about 9.40, 10.0 and 12.0 in the morning. The first was very intense and of unusual duration, six or seven minutes. It completely destroyed the lower part of the city, built on sands and clays, so that the narrow streets were obliterated under mounds of rubble. The higher part,

built on limestone, alone survived. Some 17,000 houses and 32 churches collapsed; and the churches were crowded in celebration of All Saints' Day. Curtains and woodwork falling on kitchen fires and altar candles started fires that raged unchecked for six days, completing the destruction. After the first shock many people fled from the narrow city lanes to the new marble quay beside the Tagus, but this quay, with all the people on it and the boats beside it, sank, apparently into a fissure which opened and closed again, for no bodies or wreckage were recovered. There were about 250 aftershocks in the first six months after the big earthquake.

Lisbon cannot have been far from the epicentre. Some damage to houses occurred as far away as Seville, Cordova and Granada in Spain. But shocks of intensity 10 were felt in Morocco, around Fez and Mequinez, 400 miles from Lisbon; and at Algiers, 690 miles away, the damage was little less. There were therefore two epicentres, if not three.

The disturbance of the sea floor produced large seismic sea waves, often called tidal waves (which they are not) and tsunamis or tunamis, a Japanese word. First the water receded till the bar was laid bare. Then a great wave came in, estimated at 16 to 50 feet high, sweeping half a mile inland. A number of other great waves followed, and it was four hours before the sea grew normal. The waves spread along the coasts of Portugal and Spain and reached Madeira, the West Indies, the British Isles and Holland. Tremors transmitted through the rocks set chandeliers swinging in churches over 1,000 miles from Lisbon, in Italy, Holland and Germany. They also caused rhythmic oscillations of water in lakes and canals in Switzerland, Germany, Holland, England, Scotland and Scandinavia. No other earthquake has produced such widespread and striking occurrences of these seismic seiches, as they are called.

In Japan severe earthquakes are of frequent occurrence and Japanese workers have done much to promote the science of seismology, following the pioneer work of John Milne, who was a professor at Tokyo from 1876 to 1895. There are official records of Japanese earthquakes from 800 A.D. onward. Among the great Japanese earthquakes

are those of 1891, October 28th, in the provinces of Mino and Owari, and the Kwanto earthquake of 1923, September 1st, which destroyed most of Tokyo and Yokohama. The former left a continuous trace of a fault for 40 miles across the Mino-Owari plain, passing indifferently across soft alluvium and hard rock, valley and mountain spur. The course of the fault is curved but runs in a general N.W.-S.E. direction. The north-eastern side was shifted to the N.W., with a maximum horizontal displacement of 13 feet, and it was lowered relatively by amounts up to 10 feet. At Midori, however, it was raised by nearly 20 feet, a road

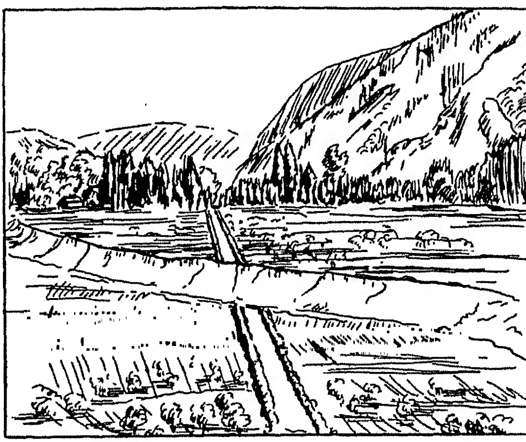

FIG. 31. Fault-scarp, Japan, 1891.

there being broken by a cliff 18 to 20 feet high and shifted 13 feet to the N.W. Where the displacement was small the fault line appeared as a low mound, as though a giant mole had been tunnelling just below the surface. Many towns and villages were completely destroyed and over 10,000 bridges were broken, girders being pushed off their piers and the piers themselves fractured. Landslides, too, were numerous.

The Assam earthquake of 1897, June 12th, is notable for the great size of the epicentral area. Practically all brick and stone buildings were destroyed over an area of 30,000 square miles. Had such a shock occurred in the English Midlands,

not a house or a bridge would be left standing between London and Liverpool. At Shillong a deep rumbling noise was heard, followed two seconds later by the shock, which lasted about one minute. It was so severe that it was impossible to stand. The land surface was seen to undulate like a rough sea, the waves seeming to be about a foot high and 30 feet long; but their velocity was greater than in sea waves. These visible waves, and the more common earthquake sounds, are both due to tremors reaching the surface and causing it to undulate, with a frequency that may be within the limits of audibility. The vertical acceleration was very great. A monolith 6 feet high was shot into the air, falling 6½ feet away, and columns were fractured and rotated on their bases. Enormous landslips were produced. Away from the epicentre the horizontal movement was greater, buckling railway lines and pushing bridges off their piers. The levels were permanently altered, so that the views from many points over intervening ridges were either enlarged or reduced; and new pools were formed. In the plains great numbers of jets of sand and water were ejected, leaving sand craters from 2 to 8 feet across.

The Alaska earthquakes of September, 1899, are chiefly notable for the changes of level that resulted from them, changes that could be directly measured from sea level. Over many miles of the coast of Yakutat Bay and its inlets elevation is proved by wave-cut benches, backed by cliffs with caves, and covered in some places by shingle and in others by masses of barnacles and mussels, left from 10 to 40 feet above the sea. At one point the elevation was 47ft. 4in., and this is the greatest change of level known to have been caused by one series of shocks. In other parts there had been some subsidence, shown by trees that had been killed by salt water.

The San Francisco earthquake of 1906, April 18th, is remarkable for the great length of the area of damage, 350 miles. It follows closely the line of the San Andreas fault, a fracture system which has been traced for more than 600 miles from Cape Mendocino in the N.W. to the Colorado Desert S.E. of Los Angeles. The continental side is mov-

ing to the S.E., or the Pacific side to the N.W., and the country has been sliced into strips, often with different

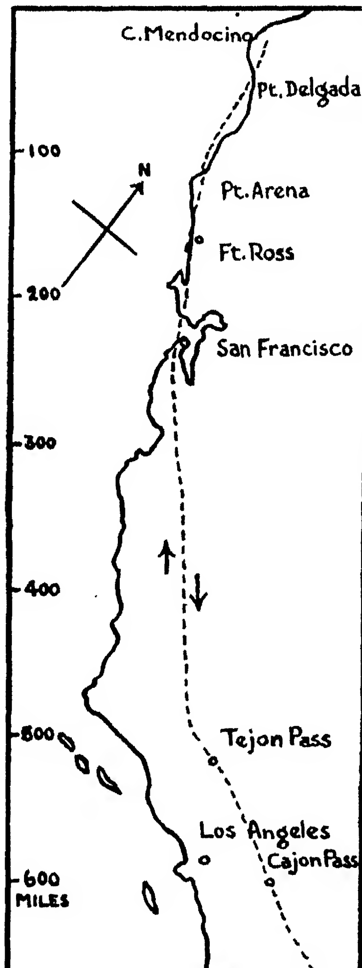

FIG. 32. Map of the San Andreas Fault, California.

geological formations on either side of the fractures. At one locality four deep ravines run down to the fault, but their lower portions have been shifted 150 feet to the N.W.

Straight fault scarps and lines of ponds are features of the fault zone. The movement in 1906 was mainly horizontal, roads and fences that crossed the fault being offset for distances of from 1 to 21 feet, but the vertical displacement was not more than 2 or 3 feet. The chief damage in San Francisco was to the low-lying parts built on alluvium and made

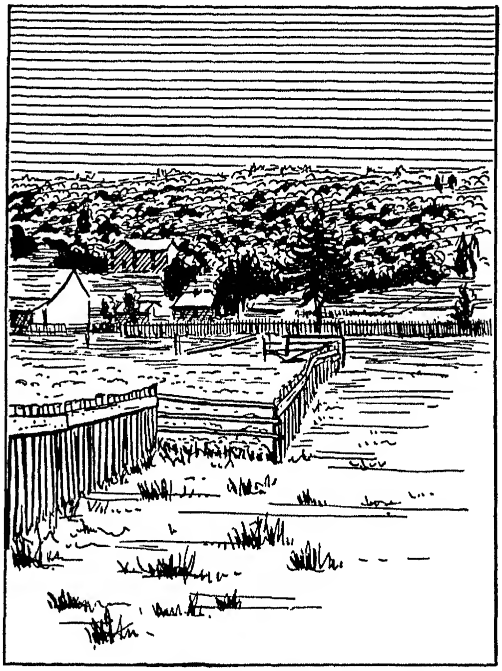

FIG. 33. Displacement of Fence, San Francisco, 1906.

ground reclaimed from the marshes. Houses built on the solid rock suffered less from the shock; but large areas of the city were burnt by fires which could only be fought by the use of dynamite, the water mains having been broken, pulled asunder or telescoped.

Many earthquakes are of submarine origin. They may be felt and heard on board ships close to the epicentre, but beyond breaking submarine cables their chief effects are the

great sea waves or tunamis they often produce. These may be 40 feet high at the point of origin but many miles from crest to crest, and on approaching land they pile up and do much damage.

The chief seismic belts follow the volcanic belts, (1) around the Pacific and (2) from Central Europe and the eastern Mediterranean to the Himalayas, Burma and the East Indian Islands. But the earthquakes are not due to

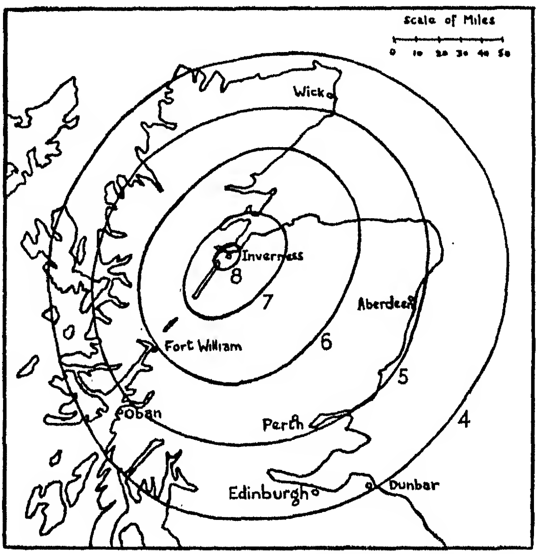

FIG. 34. Isoseismal Lines,
Inverness Earthquake, 1901. Isoseismals 8 to 4.

volcanic eruptions. Both are due to crustal movements and stresses.

In the British Isles earthquakes are most frequent along the Great Glen fault, S.W. of Inverness, and along the Highland boundary fault in the neighbourhood of Comrie in Perthshire.

It is possible to draw, for each earthquake, lines through points where equal effects were felt. These isoseismal lines usually mark the limits of the grades of the Rossi-Forel scale, and the innermost line, enclosing the meizoseismal

area where the damage was greatest, is generally an oval and sometimes greatly elongated.

Study of distant earthquakes by recording instruments called seismographs has given much information about earthquakes and also about the interior of the earth. One type of seisomograph consists of a weight attached to a horizontal boom which is pivoted at one end to a stand and supported by a wire to a point above the pivot but slightly in advance of it, so that it is just in stable equilibrium. Any displacement of the ground at right angles to the boom leaves the weight at rest, through inertia, and so the direction of the boom is varied. The displacement is magnified

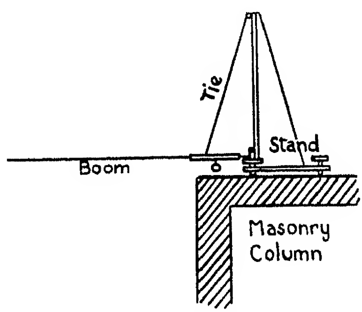

FIG. 35. A Seismograph.

and recorded, either by a long, light extension of the boom which leaves a trace on a revolving cylinder or a long strip of paper driven by clockwork, or by a mirror which throws a spot of light on to photo-sensitive paper. A complete record of earth movements can be obtained from three instruments, one recording N.-S. vibrations, one E.-W., and the third vertical. In the last the boom is suspended by a spring between the weight and the fulcrum.

If the seismograph is sufficiently sensitive, the trace on the paper is not normally a straight line. There may be rapid vibrations due to traffic or machinery, and longer-period vibrations due to the wind striking neighbouring trees or buildings. But there are also minute vibrations or

microseisms which seem to be due to waves breaking on the coast. They have periods of about 5 seconds and amplitudes of the order of 0.005 mm.; and they diminish and increase in amplitude owing to interference of different sets of waves, like beats in music.

The record of a distant earthquake begins with the arrival of the primary waves, P, which have come through the earth by the most direct route possible, though not a straight line owing to refraction. They are longitudinal waves, made

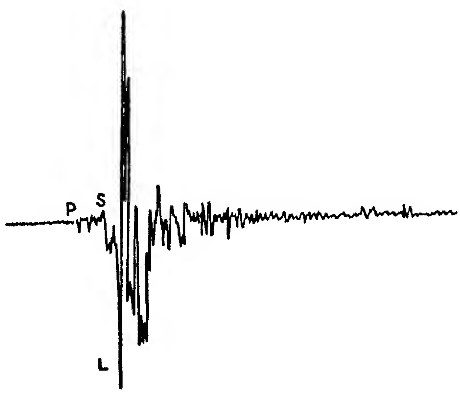

FIG. 36. A Seismogram.

up of compressions and rarefactions, or "push and pull" waves. After an interval, depending on the length of the route from the epicentre to the recording station, they are followed by the secondary waves, S, which have taken a similar course but with a lower velocity. They are transverse, distortional, or "shear and shake" waves. Then come the long waves, L, also transverse, which have kept near the surface of the earth and have longer periods than P and S; then the maximum movements, and the waning later phases. The whole record may extend over an hour or two.

The P waves resemble those which travel along a railway signal wire when the lever is pulled, and the S waves are like those in the same wire when struck transversely. Their

velocities near the surface, and apparently at depth also, are in the ratio of 1.8 : 1. Theoretically we may write

$$\text{Velocity} = \sqrt{\frac{\text{elasticity}}{\text{density}}}.$$

More precisely,

$$V = \sqrt{\frac{k + \frac{4}{3}n}{D}} \quad \text{and } V = \sqrt{\frac{n}{D}}$$

for longitudinal and transverse waves respectively, where k is the bulk modulus, n the modulus of rigidity, and D the density of the medium. Fluids have no rigidity and cannot transmit transverse waves. For longitudinal waves in fluids $V = \sqrt{\frac{k}{D}}$.

From careful analysis of the times of arrival of seismic waves at observing stations at different distances from the epicentre it is possible to plot the travel times of the waves to different distances, in such a diagram as *Fig.* 37. Then the time S – P between the arrival of the P and S waves, as shown on the seismogram, will give the distance of the epicentre; and if this is known for three stations the three circles of appropriate radius drawn around them should intersect at the epicentre.

Besides the direct body waves P and S there are others that have been reflected once or twice at the surface of the earth, designated PP and SS for a single reflection, PPP and SSS for two reflections. If the wave has changed its character on reflection it is given some such symbol as PS.

Other waves, PcP and ScS, have been reflected at a depth of about 1,800 miles (2,900 km.), below which is a central core which seems to have no rigidity. Transverse waves cannot pass through it: their energy is partly reflected and partly transmitted as longitudinal waves. The symbol K (for the German Kernwellen) is used to represent waves that have passed through the core, PKP, PKS, etc. It is owing to this core that the direct P and S waves die out at about 105° from the epicentre.

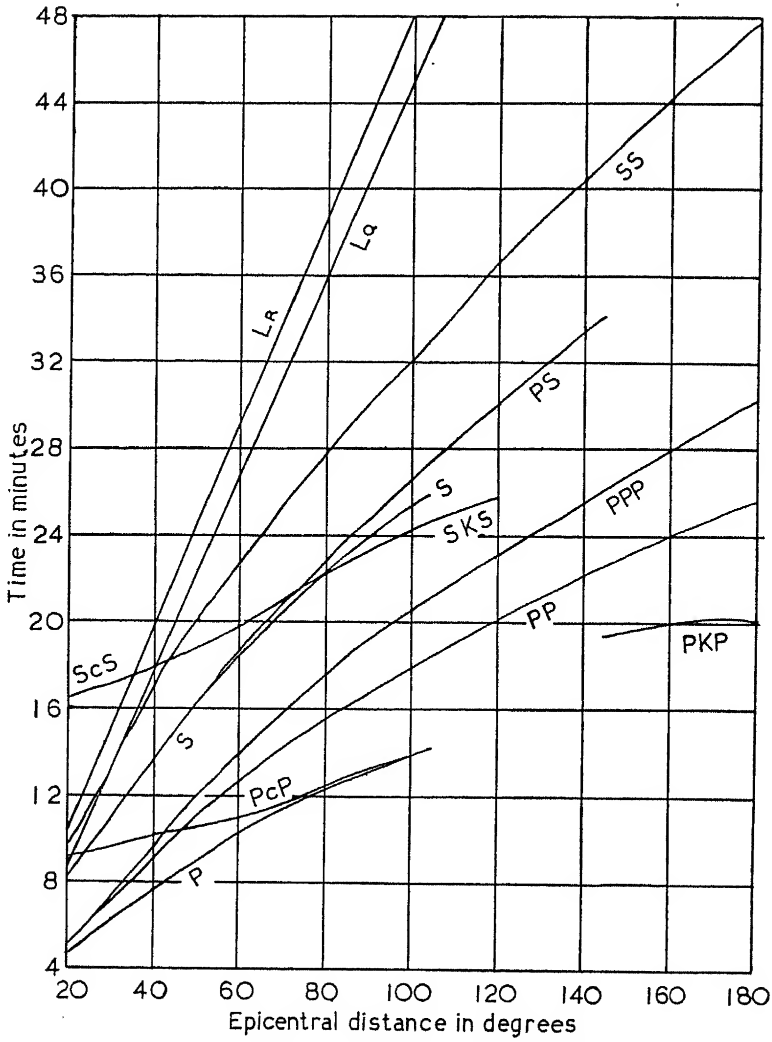

FIG. 37. Times of Travel of Seismic Waves.

The surface waves, L, are of two types. The faster Love waves, L_Q (Querwellen), have horizontal oscillations while the Rayleigh waves L_R are in a vertical plane.

In normal earthquakes the focus lies within 30 miles (50 km.) of the surface, with an average depth of about 20 miles. But a few earthquakes originate at ten times that depth. These deep earthquakes are characterised by the absence of surface waves, abnormal travel times of the body waves, and uniform effects over a very large area around the epicentre. It is hard to conceive of rocks fracturing at

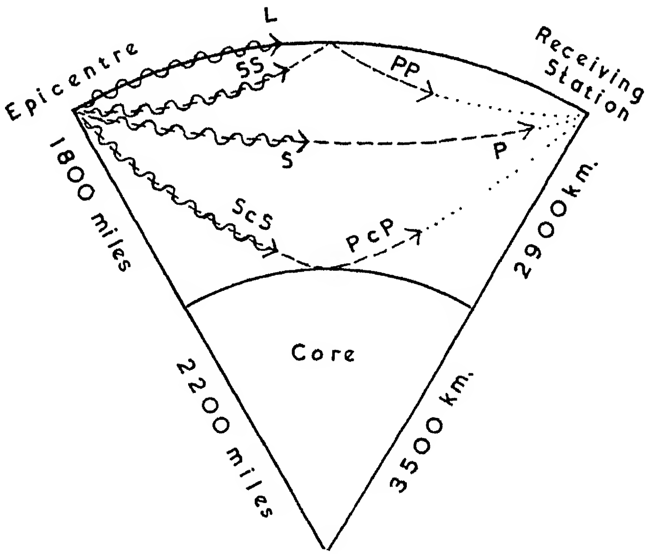

FIG. 38. Paths of Seismic Waves to a station 60° from epicentre.

such depths as 200 miles. Possibly changes in crystalline state may originate these deep-focus shocks.

We may now summarise what has been learnt from various sources about the earth's interior. The density of the earth as a whole is 5.6, while the rocks of the crust average about 2.6, so the central part must have a very high density and is probably metallic. The composition of meteorites suggests that it is largely iron and nickel. Around this

metallic core lie dense silicate rocks, with less dense rocks forming the outer crust. From this increase of density with depth we might expect seismic waves to travel more slowly the deeper they penetrate; but the velocity actually increases with depth, so that the rigidity of the rocks must increase even more than their density. But rather less than half-way to the centre of the earth this rigidity is lost, and the core is presumably plastic. There is no continuous liquid layer that might supply magma to volcanoes.

In the crust we find relatively light rocks such as granite, sandstone, clay and limestone, resting on denser rocks of basaltic composition; and at greater depths there is evidence of still denser rocks, peridotite and eclogite. The lighter rocks have been dubbed sial, from the *si*lica and *al*umina abundant in them, and the basaltic layer is sima, from *si*lica and *ma*gnesia. Similarly the metallic core is called nife (Ni and Fe). The ocean floors are of sima with only a thin layer of sediments, while the continents are masses of sial, which is fairly thin under low-lying country but very much thicker under mountainous regions. Thus the greater mass is compensated by the lower density of the material. These matters are discussed in rather more detail in Chapter XIII.

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CHAPTER IX

DIP AND STRIKE

MOST sedimentary rocks were laid down in approximately horizontal planes, on the floor of a sea or lake. But in many places we find that tangential pressure has forced them up and given them a tilt. In this chapter we deal only with areas small enough for the tilt to be assumed constant.

All horizontal lines that can be drawn in a tilted bedding plane are parallel to one direction, the line of strike. At right angles to this is the direction of dip, the steepest slope

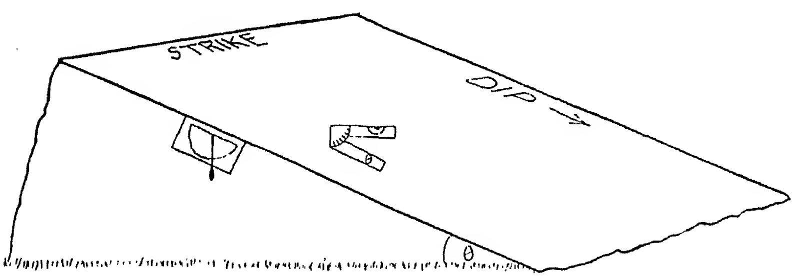

FIG. 39. Dip and Strike.
Showing also two types of Clinometer.

in the bedding plane. The amount of dip is the angle between the bedding plane and the horizontal. Thus finding the dip involves the determination of two angles, one horizontal and the other vertical. We may for example have a dip of 18° in a direction N. 22° E. (or N.N.E.).

Dips are measured by means of clinometers. A simple clinometer may be made by gluing a semicircular protractor to a rectangle of wood, with its diameter parallel to an edge, and pushing a drawing pin through the centre. To this a thread bearing a small plummet is fastened so as to hang across the protractor, which should be marked 0° at the lowest point and 90° at each end. If this instrument is held

between the eye and the rocks exposed in a cliff or quarry, so that the top coincides with the bedding, the thread will mark the angle of dip. The direction of dip is given by a compass, allowance being made for the declination or angle between magnetic and true north.

In most clinometers the plummet and compass needle are carried on a single axle at the centre of a watch-like instrument with a straight edge fixed at right angles to the 0° direction of the dial. Another type consists of two arms hinged together, with a quadrant at the hinge divided into degrees to measure the angle between the arms. One arm is

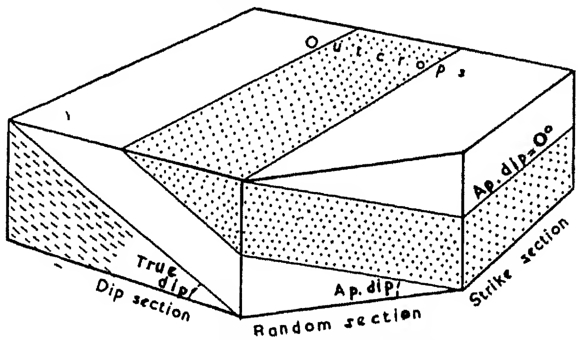

FIG. 40. True and Apparent Dip.

held parallel to the bedding, or is laid on an exposed bedding plane in the direction of the true dip, and the other arm is set horizontal, as indicated by a spirit level contained in it.

It cannot be assumed that a random section, such as a railway cutting, lies in the direction of true dip. Any other direction will give an apparent dip which is less than the true dip; and in a section along the strike the beds will seem to be horizontal. But the true dip can be found from two apparent dips measured on any two exposures which are not parallel. The procedure is as follows:—

(1) Plot the two directions AB and AC (*Fig.* 41) in which the apparent dips have been measured, so that both dip away from A, the point of intersection, or both toward it.

(2) At A draw AD perpendicular to AB, and AE perpendicular to AC, making AD=AE.

(3) At D make ∠ADK equal to the complement of the angle of dip along AB (*i.e.*, 90° *minus* dip) and let DK cut AB at K.

(4) Similarly at E make ∠AEL equal to the complement of the angle of dip along AC, and let EL cut AC at L.

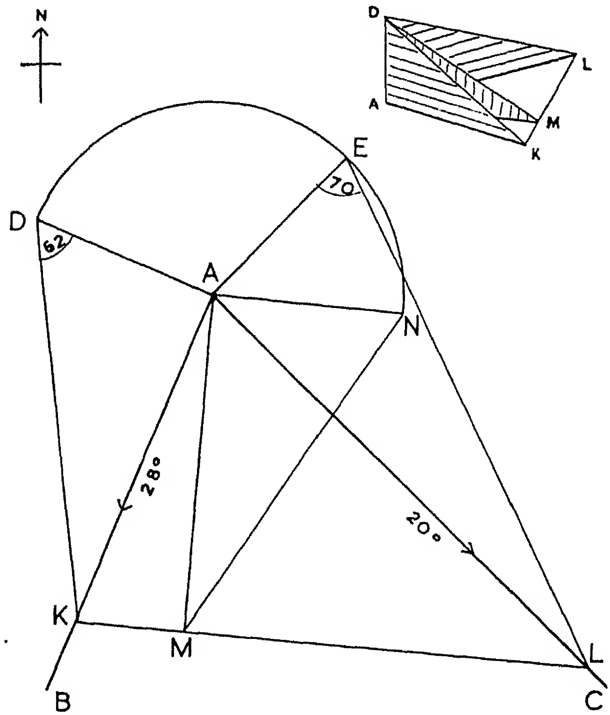

FIG. 41. Determination of True Dip from two Apparent Dips.

(5) Join KL. This is the line of strike. For consider the triangles ADK and AEL turned up vertically, so that AD and AE coincide, then DK and EL will both lie in a bedding plane which cuts the horizontal plane in the line KL, which must therefore be the direction of strike.

(6) Draw AM perpendicular to KL. AM is clearly the direction of true dip.

(7) Draw AN perpendicular to AM and equal to AD or AE. Join MN. Then the angle AMN is the angle of true dip. For if the triangle AMN is set vertical, MN also lies in the bedding plane.

The example depicted in *Fig.* 41 is based on two apparent dips of 28° to the W.S.W. and 20° to the S.E. The true dip is found to be 30° in a direction S. 5° W. If the reasoning is not quite clear the student should draw the figure on a larger scale on cardboard and cut it out, drawing a knife along AK and AL to make the triangles turn up. He should

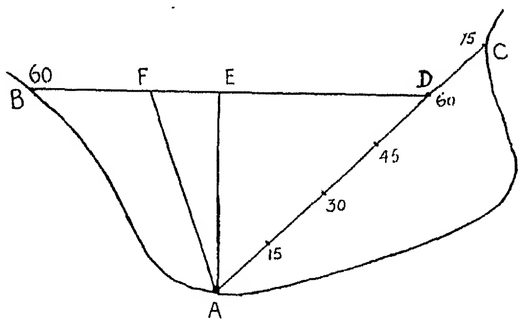

FIG. 42. True Dip found from three points the relative heights of which are known.

also find the true dip from the following pairs of apparent dips:—

(1) 18° to the E.N.E. and 12° to the S.E.*
(2) 21°, S. 18° W. and 25°, S. 51° E.
(3) 13° to S.S.E. and 5° to W.S.W.
(4) 30° to N.W. and horizontal on an E.—W. face.
(5) If the true dip is 42°, what is the apparent dip seen in a section 30° from the line of dip?

The true dip can also be found from three points in a bedding plane, not in a straight line, the relative heights of which have been determined. Thus the curved line BAC in *Fig.* 42 may represent the top of a hard bed cropping† out

* (1) 20°, E. 3° N. (2) 27°, S. 22° E. (3) 15° S. (4) 38° N. (5) 38°.

† The common use of "outcrop" as a verb is to be deplored. It is contrary to English usage, like "it outcame" for "it came out"; and, moreover, such expressions as "the coal outcrops" have an ambiguity which is avoided by "the coal crops out."

on a hillside. A survey has shown that A is 60 feet below B and 75 feet below C. Join AC and divide it into five equal parts. If the dip is constant the four intervening points must be 15, 30, 45 and 60 feet above A; and if D, the last of them, is joined to B the line BD gives the strike, for it lies 60 feet above A throughout. EA, drawn perpendicular to the strike, gives the direction of dip. The angle of dip, θ, is such that $\tan\theta = 60/EA$. It may also be found by making EF, perpendicular to EA, equal to 60 feet on the scale to which the map is drawn, joining FA, and measuring the angle FAE.

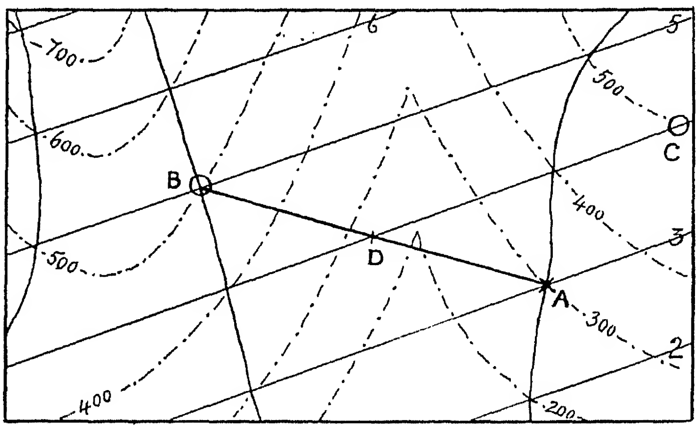

FIG. 43. Stratum Contours and Outcrop found from three points of known elevation in a seam.

In other forms of the three-points problem some or all of the points are obtained from shafts or borings instead of surface outcrops. Thus in the map, *Fig.* 43, a thin seam of coal crops out at A and is found 100 feet below the surface at B and 200 feet below the surface at C. It lies therefore at 200, 400 and 300 feet above Ordnance Datum at A, B and C respectively; and a line joining C to a point D midway between A and B must be a strike line and also the 300-foot contour in the seam. The direction of dip is 27° E. of S., and its amount depends on the scale of the map.

Lines drawn parallel to DC through A and B will mark the 200 and 400-foot contours of the coal seam, and other equidistant parallel lines may be drawn for the 500, 600, 700 . . . stratum contours. From this it is an easy step to plot the outcrop of the seam. All points where the 300-foot stratum contour cuts the 300-foot surface contour lie on the outcrop, and so do all points where the 400, 500 . . . contours intersect corresponding surface contours. If all such

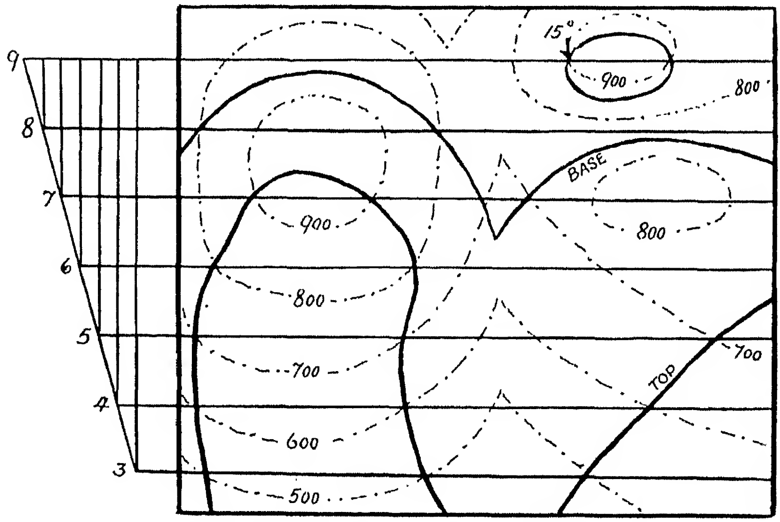

FIG. 44. Stratum Contours and Outcrop found from True Dip.

points are joined by smooth curves these will approximate to the outcrop of the seam, always assuming that the dip remains constant throughout the area represented by the map.

In the next map, *Fig.* 44, the base of a bed 200 feet in vertical thickness crops out at the point represented by the tip of the arrow and dips south at 15°. It is required to trace the outcrop of the bed. This problem may be solved by drawing through the arrow-tip an E.-W. line which marks the 900-foot stratum contour in the base of the bed. On this line mark off eight points 100 feet apart on the scale of the map. Through seven of the points draw perpendiculars to

the strike line, and through the eighth draw a line at 75° from it, intersecting the others. Then if the triangle so formed is set vertical, it will be seen that the other lines mark the position of horizontal planes 800, 700, 600 . . . feet above Ordnance Datum, and their intersections with the bedding plane (the hypotenuse of the triangle) show where the corresponding stratum contours lie. Draw these contours parallel to the 900-foot line, and join up all points where they cut the corresponding surface contours. This will give the outcrop of the base of the bed. Since the bed is 200 feet in vertical thickness, the 600-foot contour in the base will become the 800-foot contour in the top of the bed, and so on. Altering all values of the stratum contours by 200 feet we may trace the outcrop of the top of the bed in the same way as the base; and the area between these two lines may be coloured as the outcrop of the bed.

In working these and similar exercises two rules must be rigidly observed: (1) the line of outcrop must not cross any stratum or surface contour except where they intersect, and (2) it must cross both contours at such points, passing from the higher side of each to the lower, or *vice versa*.

Given a contour map with geological boundaries marked on it, it is not a difficult problem to read the structure. Draw as many stratum contours as possible through points where the same line of outcrop cuts the same contour. If the stratum contours are equidistant, and rise or fall in the same direction, the dip is constant. The direction of dip is at right angles to these strike lines, and its amount is found from their distance apart. If for instance the 100-foot stratum contours are separated by a distance equivalent to 400 feet on the scale of the map, the dip θ is such that $\tan \theta = 0.25$, whence θ is found from a table of natural tangents or graphically to be 14°.

The map in *Fig.* 44 may be worked backwards. Given only the surface contours, the outcrop, and the scale of the map, the stratum contours can be drawn and from them the dip can be found. The vertical thickness of the bed is obviously 200 feet, since any stratum contour passing through both boundaries shows the base 200 feet lower than the top. The true thickness is of course 200 cos 15°, or 192 feet.

In one form or another, complicated by unconformities, faults, and unnaturally angular folds, these problem maps afford useful practice in the relation between dips and outcrops. They are, however, merely geometrical exercises with a geological application, not geological maps; and they have received undue importance through being included in most practical geology examinations in this country. All examination candidates should therefore work through as many examples as possible. A series of elementary maps by J. L. Platt is published by Thomas Murby and Co., London, and maps set by the University of Cambridge are also obtainable.

Any student who is unable to "see solid" in these two-dimensional maps may make a useful model out of a cardboard shoe-box. First rule lines parallel to the bottom, at

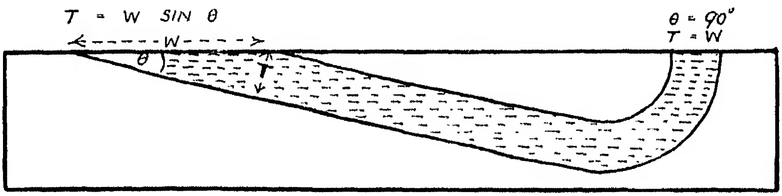

FIG. 45. Width of Outcrop affected by Dip.

half-inch intervals, on all four sides. At the ends draw diagonal lines to represent traces of a bedding plane, and make holes where they intersect the horizontal lines. Coloured threads passed through the holes from end to end will serve as stratum contours. Surface contours, representing hills and valleys, may be indicated by threads passing from side to side of the box; and the intersections may be joined to show the outcrop.

Where the bedding is horizontal geological boundaries do not cut any contours. They behave like contour lines, with V-shaped forms pointing upstream where they cross valleys. Beds dipping into the hills have less sinuous outcrops than the contours, with blunter Vs pointing upstream. Beds dipping away from the hills V upstream if the valley floor falls more steeply than the dip, downstream if the dip is

steeper than the valley. Vertical beds cut across country in the line of strike, with no deviation for hills and valleys, and their outcrop is as wide as the beds are thick.

The width of outcrop (w) of a bed depends on its thickness (t), the dip (θ), and the slope of the ground. On level ground $t = w \sin \theta$, and for a given width of outcrop the thickness increases with the dip to a maximum of $t=w$ where $\theta=90°$. But on a steep declivity the outcrop may be very much narrowed; and outcrops in a cliff are usually unmappable.

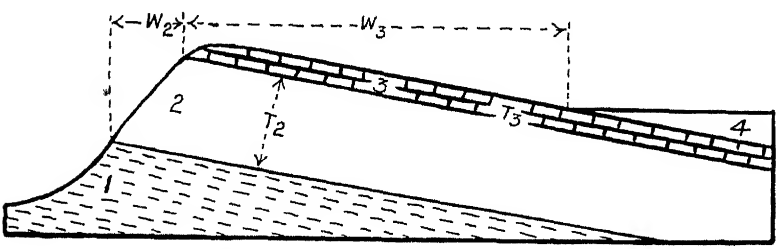

FIG. 46. Width of Outcrop affected by Relief of Ground. Escarpment and Dip-slope.

With increasing dip the Chalk outcrop in Surrey narrows from a width of seven miles south of Croydon to a quarter of a mile in the Hog's Back, where the dip rises to 55° at one point.

A thin bed that resists erosion better than beds above and below it often shows an unduly wide outcrop. Thus the thin limestone of the Cornbrash has in many districts been denuded of the overlying clay, giving a wide dip-slope, while it terminates in a short steep slope or escarpment due to the greater erosion of the beds below. More imposing escarpments and dip-slopes are seen in the Eglwyseg Rocks near Llangollen (formed of Carboniferous Limestone), Wenlock Edge (Wenlock Limestone), and the Cotteswold Hills (Inferior Oolite). The Chalk dip-slopes rise to escarpments in the Chiltern Hills and the North and South Downs, and the Lower Greensand escarpment is well seen in Leith Hill and Hindhead.

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CHAPTER X

FOLDS

IN the majority of cases dipping strata form one limb of a fold, and they often lie between an upfold or anticline and a downfold or syncline. At its inception an anticline may form a ridge, and a syncline a valley; but denudation generally leads to inversion of relief. This is because the beds at the crest of an anticline are in a state of tension; the joints are opened, letting in rain and promoting erosion as compared with the rocks in a syncline, which are in a state of

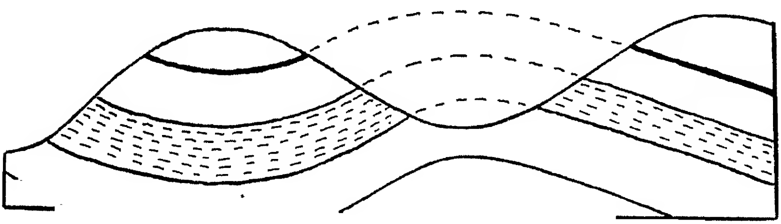

FIG. 47. Inversion of Relief.
Synclinal Ridge and Anticlinal Valley.

compression. So an anticline is frequently eroded into a valley while a syncline may form a ridge.

In an eroded anticline the oldest rock is exposed at the centre, flanked by younger rocks on either side. But in a syncline the youngest bed occurs at the centre, with older rocks on the outside.

In France the term *fond de bateau* is sometimes used for a syncline and *fond de bateau renversé* for an anticline. Just as a boat may roll and pitch, so the axial plane of a fold may diverge from the vertical and its axial line, like the keel, may diverge from the horizontal. Moreover, the sides generally close in fore and aft, and the fold does not run on indefinitely.

Folds with horizontal axes, cut by a horizontal surface, show parallel outcrops; but if the axes pitch away from the horizontal the outcrops become horseshoe-shaped. Many folds pitch at both ends, with oval outcrops; and the oval

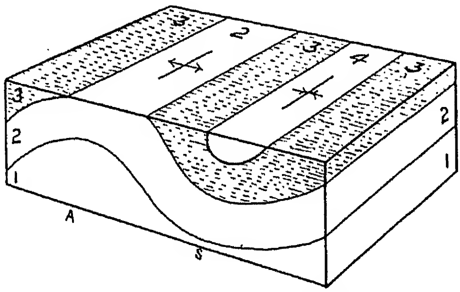

FIG. 48. Anticline and Syncline.

approaches a circle in a dome (pericline, or quaquaversal dip). The Mendip Hills, for example, are a series of four elongated domes *en échelon,* with Old Red Sandstone forming the cores and Carboniferous Limestone dipping steeply

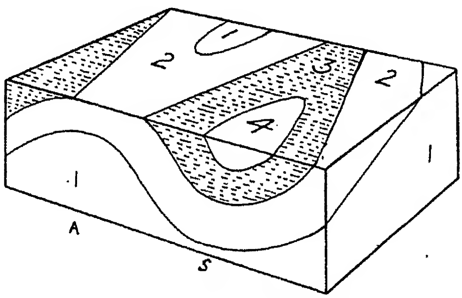

FIG. 49. Pitching Folds.

away on either side and at the ends. Conversely, in a basin the beds dip inward toward the centre.

The block diagram, *Fig.* 49, shows the outcrop of pitching folds on a horizontal surface; but if the surface is inclined, a mountain side, for example, it will be seen that a pitching anticline may be mistaken for a syncline and a pitching syncline for an anticline. One may also get a false

impression of an anticline in the cliffs of a bay cut in strata with a constant dip to seaward, while an inland dip may simulate a syncline under like conditions.

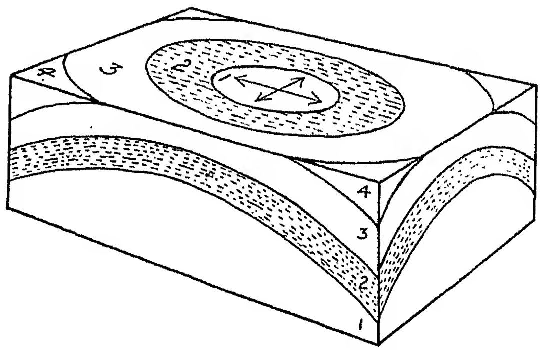

FIG. 50. Dome or Pericline.

The axial plane of a fold may be vertical or inclined, or even horizontal, and the beds on either side may be symmetrical or asymmetric. One limb may be short and steep,

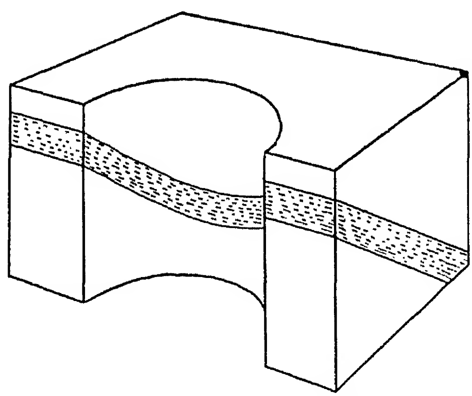

FIG. 51. False Suggestion of a Syncline in a Bay cut in Beds with a constant Dip Inland.

the other long and slightly inclined. A monocline is an extreme case of this sort, an abrupt steep dip flanked by nearly horizontal strata, as in the Isle of Wight, where the Oligo-

cene beds in the north have a slight southerly dip but the Eocenes and Chalk of the central part are vertical or near it, while the gentle dip to the south is resumed in the southern part of the island. In America, however, the term monocline is sometimes applied to a single group of tilted strata not forming part of any obvious fold, such as the Cotteswold Hills.

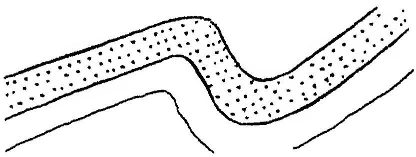

FIG. 52. Asymmetric Folds.

If the beds in one limb of an anticline have been turned through more than 90° from the horizontal, so that older beds overlie younger, the fold is said to be overturned. If the angle approaches 180° the fold is a recumbent one. The tip of a recumbent anticline may sag, simulating a syncline.

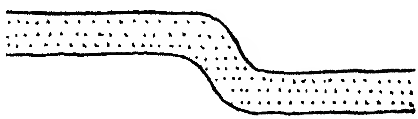

FIG. 53. Monocline.

A succession of folds, the limbs of which all have the same dip, is known as isoclinal or concertina folding. The crests of the folds may have been eroded and the troughs hidden from view, so that the effect is that of a very great thickness of undisturbed strata. Even when the repetition of beds in reversed order (*e.g.*, 3, 2, 1, 2, 3, 2, 1) has been noticed, it may be difficult to determine which was originally the top of the series and which the bottom (see p. 185).

A series of minor folds forming a major arch is known as an anticlinorium, or fan structure, as in the Southern Up-

lands of Scotland. Inward dips are usual on the flanks of an anticlinorium and may cause the structure to be misinterpreted as a syncline. A similar series of minor folds with a sag instead of an arch is a synclinorium, such as that of Devon.

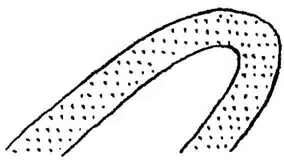

FIG. 54. Overfold.

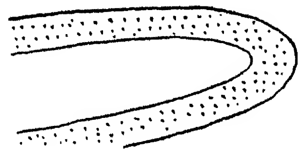

FIG. 55. Recumbent Fold.

Geosynclines are very large areas that sink as deposits accumulate on them. Similar wide elevations are geanticlines. It is useful to distinguish between a cuvette, or basin of deposition which sagged as deposition proceeded, from a structural basin. The London Basin and the Kent Coalfield are cuvettes though there was also subsequent folding.

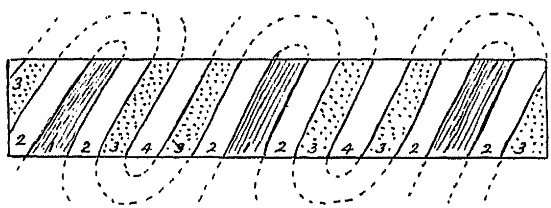

FIG. 56. Isoclinal Folding.

The immediate cause of folding is generally pressure acting tangentially to the earth's surface. Radial pressure, upward or downward, results in fracture and tilted fault blocks, but rocks affected by tangential pressure are thrown into folds and so cover a reduced area. Before the Devon synclinorium was formed, the rocks of Plymouth were many miles farther away from those of Ilfracombe than they are to-day. More intense pressure may produce overfolds many

miles in length, and fracture will permit the upper limb to travel farther, with overthrusting and the production of nappes, as described in the next chapter.

A sharp bend in a thick series of rocks involves certain strains. Rocks on the outer or convex side of the bend are in a state of tension, those on the concave side are compressed. Minor adjustments, such as little slips along suc-

FIG. 57. Anticlinorium.

FIG. 58. Synclinorium.

cessive bedding planes, may relieve some of the strain; and there is a tendency for softer, incompetent rocks to be squeezed out. Clays, rock-salt and gypsum behave like plastic substances under pressure.

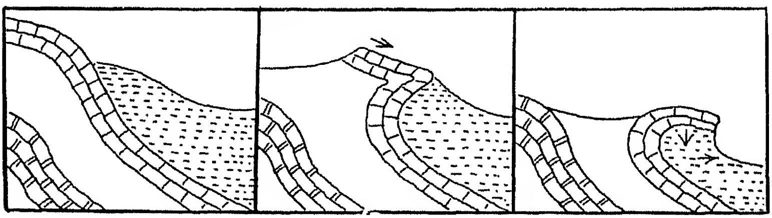

FIG. 59. Stages in the Development of Gravity Collapse Structures.

Limestones overlying clays often show an arched structure on ridges, owing to the clay yielding on either flank. And in valleys clays may bulge up, with the overlying beds, into a pseudo-anticline owing to the reduced pressure there. The London Clay and the Weald Clay sometimes show quite sharp folding which is of purely superficial origin.

When massive limestones or sandstones, lying between incompetent clays or marls, are steeply inclined, gravity may cause them to collapse, squeezing out the incompetent

beds and forming structures that are only indirectly due to crustal forces. *Fig.* 59 shows three stages in the formation of a flap through collapse of the upper band of limestone.

Another type of structure indirectly connected with crustal movement is seen in the salt domes of some oilfields. Under pressure salt is highly plastic and may force its way upward in a cylindrical plug, lifting a cap of rock and upturning the beds on its flanks. The salt may be extruded at the surface, forming a hill from which it flows outward in salt glaciers over the surrounding rocks.

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CHAPTER XI

FAULTS

WHEN rocks cannot adjust themselves to crustal pressure by folding they break, with relative movement on either side of the fracture, or fault as it is called. The movement may be vertical, oblique or horizontal, as we have seen in Chapter VIII; but in the absence of indications to the contrary vertical movement is assumed and the two sides of the fault are called the upthrow and downthrow sides respectively.

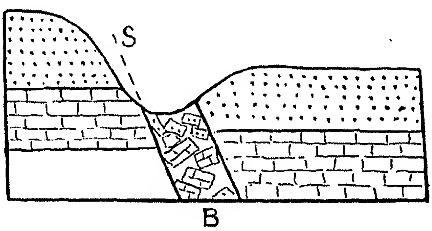

FIG. 60. Fault with Shatterbelt.
S—Fault scarp. B—Fault breccia.

Vertical movement unconnected with folding may give rise to faulted plateaux, as in East Africa, and block mountains like those of the Great Basin in the Western United States (*Fig.* 83, p. 96).

The movement may groove, striate and polish the rocks on either side of the fault, which are then said to show slickensides. The striations indicate the direction of movement. But there may be a belt of shattered rock which forms a fault-breccia when cemented. The movement may not be confined to a single fracture but distributed over a number of lesser faults.

The angle which the fault-plane makes with the vertical is called the hade of the fault. The vertical displacement of

the beds is the throw and the horizontal displacement is the heave of the fault. The movement along the fault-plane is the slip.

The movement may give rise to a fault-scarp (p. 54), but such features are usually temporary and soon eroded away. A resistant rock thrown down against softer beds may in time form a reversed fault-scarp overlooking the more rapidly eroded beds on the upthrow side of the fault. But in many cases the fault line is hard to trace at the surface. It may be marked by a line of springs if it offers a passage for water through impermeable strata; or it may form a shatter-belt easily eroded into an inlet on the coast or a valley inland;

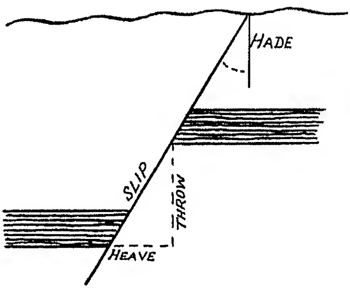

FIG. 61. Normal Fault.

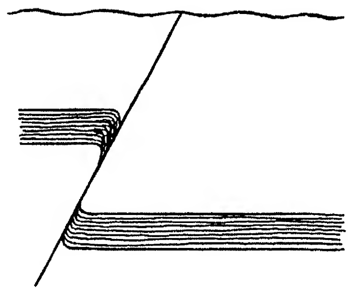

FIG. 62. Reversed Fault.

and the different nature of the beds on either side may be evident to the casual observer or after careful mapping.

Faults are shown on maps by heavy lines, usually in white, blue or black. Faults met with underground, as in colliery workings, are marked in yellow. Often a yellow line parallel to a white line will show the direction in which the fault hades. The downthrow side may be marked by a short stroke at right angles to the fault line; but it can be recognised wherever two different beds lie on either side of the fault as the side of the younger rock, for clearly younger rocks are thrown down against older and not *vice versa,* unless the beds are inverted.

Faults, whether in horizontal or inclined strata, may be divided into normal faults, which hade toward the downthrow side, and reversed faults, which hade toward the up-

throw. These terms originated in the English coalfields and it must not be inferred that normal faults are commoner than reversed faults throughout the world. It will be seen from *Figs.* 61 and 62 that a vertical boring through a normal fault may give no indication of a bed, while in a reversed fault it

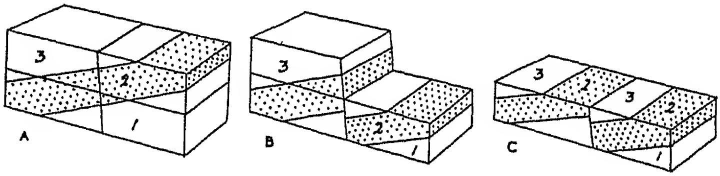

FIG. 63. Strike Fault. Outcrops repeated.
A—before faulting. B—immediately after faulting. C—after erosion.

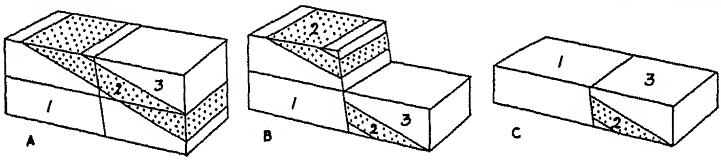

FIG. 64. Strike Fault. Outcrops cut out.
A—before faulting. B—immediately after faulting. C—after erosion.

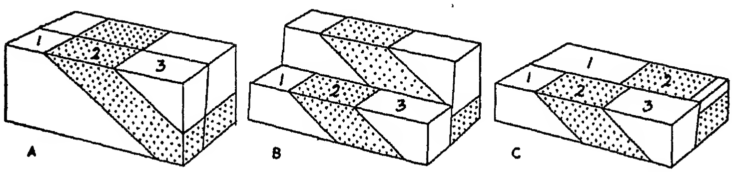

FIG. 65. Dip Fault.
A—before faulting. B—immediately after faulting. C—after erosion.

may pass through the same bed twice. Moreover, if the black bed in these figures represents a seam of coal, the acreage of coal is reduced below expectations by a normal fault and increased by a reversed fault.

From the structural point of view, normal faults are due to tension and the beds occupy more space than they did before faulting; while reversed faults are due to compression and reduce the space occupied by the beds.

Faults in inclined strata may also be divided into strike faults and dip faults, according as they run nearly in the direction of the strike or the dip of the beds. A strike fault with downthrow against the dip undoes the work of the dip and may cause repetition of outcrops (*Fig.* 63); and a strike

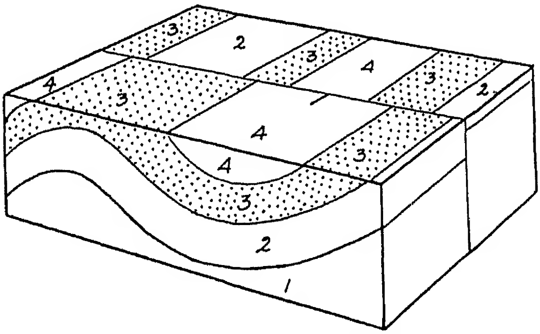

FIG. 66. Folds Faulted Transversely.

fault with downthrow in the same direction as the dip may cause outcrops to be omitted (*Fig.* 64). A dip fault displaces the outcrops on the downthrow side in a direction against the dip (*Fig.* 65), unless the ground slopes in the direction

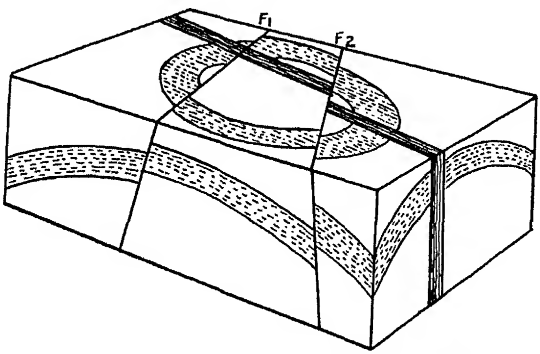

FIG. 67. Normal Fault and Tear Fault.

of the dip and at a steeper angle. In all these diagrams note that the younger rock is on the downthrow side of the fault.

A faulted anticline is narrower on the downthrow side, because an arch narrows upward and the outcrops are shifted

against the dip; but a faulted syncline is wider on the downthrow side.

If the movement is horizontal, there is, of course, no downthrow side and attempts to find it lead to discordant results. *Fig.* 67 represents a dome traversed by two faults. That on the left, F_1, is a normal fault with vertical movement; the outcrops are narrowed on the downthrow side, and the verti-

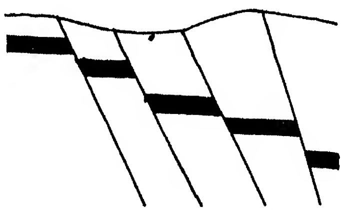

FIG. 68. Step Faults.

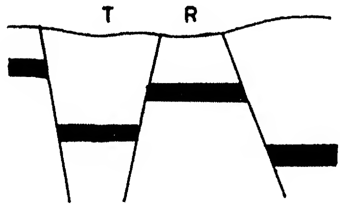

FIG. 69. Trough Faulting and Ridge Faulting.

cal dyke is not shifted by the fault. In the other fault, F_2, the movement is purely horizontal; all outcrops, including the dyke, are shifted equally, there is no narrowing of outcrops, and the younger rock lies to the right of the fault at the back of the block and to the left at the front. Faults with horizontal movement are sometimes called tear faults.

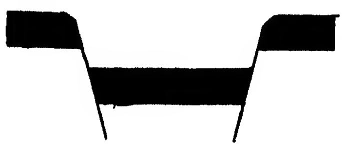

FIG. 70. Rift Valley or Graben.

FIG. 71. Horst.

A fault may split into two or more branches. Groups of more or less parallel faults also occur. In step faulting they all throw the beds down in the same direction, so that a bed occurs at successively lower levels, like the treads of a staircase. In trough faulting the beds are let down between two faults and in ridge faulting they are let down on each side of a central mass. A fault trough forming a topographic depression is a rift valley or graben, and a ridge fault forming a topographic elevation is a horst. With normal faulting all

these are due to tension; but compression may form similar structures with reversed faults.

A reversed strike fault with its plane approaching the horizontal is known as an overthrust. It may represent a recumbent fold the middle limb of which has been pinched out. The overthrust mass is called a nappe, which is French for a sheet. In the Alps such nappes have been pushed many miles from south to north and piled one above another. In North-West Scotland the Glencoul, Ben More and Moine nappes have been driven westward, each over its own thrust plane, so that Pre-Cambrian rocks lie above Cambrian. Beneath the Glencoul thrust is a zone in which many small

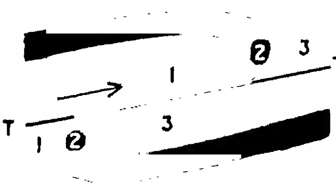

FIG. 72. Overthrust.

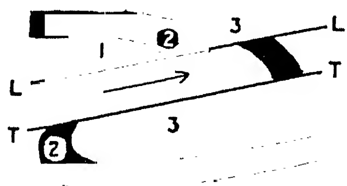

FIG. 73. Lag Fault (LL).

reversed faults have produced slices of Cambrian rocks overlapping like tiles on a roof (imbrĭcate structure). This is separated by a basal thrust, the sole, from the rocks of the foreland, the resistant block that has been overridden by the successive nappes. (See *Fig.* 166.)

In regions of thrusting, the rocks between two faults may have been driven farther than the overlying beds, which lag behind. The upper fault is then called a lag fault: it might be called an underthrust. It resembles a normal fault but is due to compression, not tension.

The fault that runs through Glen More, the Great Glen of Scotland, has been regarded as a normal fault with downthrow to the south-east, but a later view is that it is a tear fault on a large scale. The southern part of the Strontian granite has, it is claimed, been carried some 65 miles to the north-east to the neighbourhood of Foyers. The Midland Valley of Scotland is a wide fault trough between the High-

land Boundary fault and the series of step faults known as the Southern Boundary fault.

The Pennine, Dent and Craven faults are important dislocations in Northern England. The Bala fault in Merioneth seems to be a tear fault with horizontal movement of some five miles. The Church Stretton fault has a throw of many hundred feet. A number of small faults are well exposed in the cliffs of Dorset.

In Belgium and Northern France colliery shafts pass through Devonian rocks that have been thrust over Coal Measures along a reversed fault, the *Grand Faille du Midi.* The most famous examples of rift valleys are in East Africa, the Jordan Valley, and the Rhine Valley between the Vosges and the Black Forest. And the San Andreas fault in California is the best-known tear fault.

CHAPTER XII

OTHER STRUCTURAL DETAILS

1. UNCONFORMITY

ON a subsiding sea floor pebble beds may be covered by sands and sands by clays as the water deepens, but so long as there is no break in deposition the beds form a single conformable series. Unconformity connotes a break in the continuity, a line or a page missing from the geological record. If the beds come within the range of wave action, erosion may take the place of deposition, to be followed on

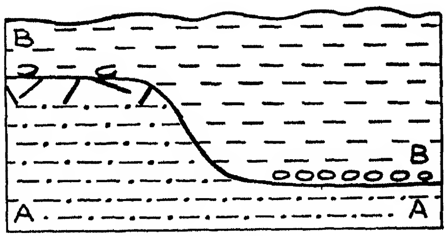

FIG. 74. Unconformity in Horizontal Strata.

further subsidence by a renewal of sedimentation. Such a break, with the bedding planes of the new deposits parallel to the old ones, is known as a non-sequence, disconformity, or stratigraphical unconformity. It may or may not be marked by a line of pebbles or of phosphatic nodules, or by an abrupt change in the fossil fauna or in the type of deposit. The top of the older bed may show borings made by molluscs or worms, and oysters may be attached to it. Several non-sequences occur in the Inferior Oolite of the Cotteswold Hills; and even the far greater interval that separates the Cretaceous rocks from the Eocene in England is marked by no apparent difference in dip between the two series.

If the older beds have been eroded into channels, cliffs or valleys, the unconformity is more noticeable.

With a greater time interval the older beds may have been folded, faulted, cut by igneous dykes, or even metamorphosed, before the newer series was deposited. The two series

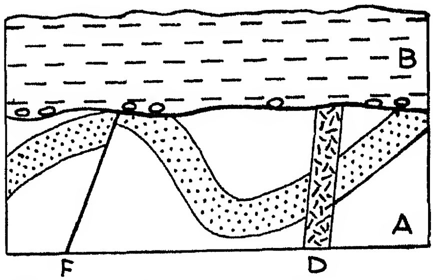

FIG. 75. Unconformity with Angular Discordance.

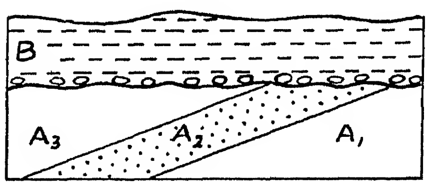

FIG. 76. Overstep.

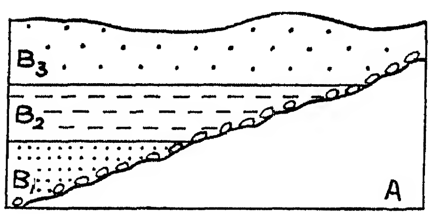

FIG. 77. Overlap.

then show different dips: there is angular discordance. Striking examples of this are seen in the nearly horizontal Upper Old Red Sandstone resting on upturned Silurian rocks at Siccar Point, south of Dunbar, Carboniferous Limestone on Silurian at Arco Wood Quarry near Settle in Rib-

blesdale, and Inferior Oolite on the Carboniferous Limestone of the Eastern Mendips.

Discordance is often accompanied by overstep, the newer deposits passing in succession over the eroded edges of different members of the older series.

Gradual subsidence of the older rocks may have caused a slow advance of the sea in which the newer series was deposited, and the later members of that series overlap the

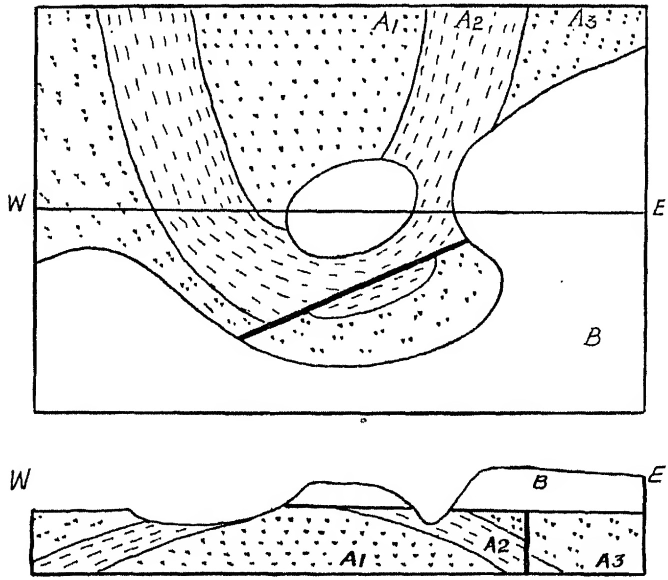

FIG. 78. Unconformity, in map and section.

earlier ones. The local base of the series is not everywhere of the same age.

The unconformity below the Cretaceous rocks, with Gault and Upper Greensand overlapping the Lower Greensand and overstepping in succession all the Jurassic rocks from Portlandian to Lias, is well shown in the One-Inch maps of the Geological Survey, Sheets 282 (Devizes), 313 (Shaftesbury), and 326 (Sidmouth).

2. INLIERS

An outcrop of older rocks isolated from the main mass and surrounded by younger beds is called an inlier. It may be due entirely to erosion of the overlying beds. Thus the valleys running northward from Leith Hill in Surrey are mainly in porous Hythe Beds; but their floors are boggy in places where the underlying Atherfield Clay is reached in valley inliers (Geol. Surv. Sheet 286).

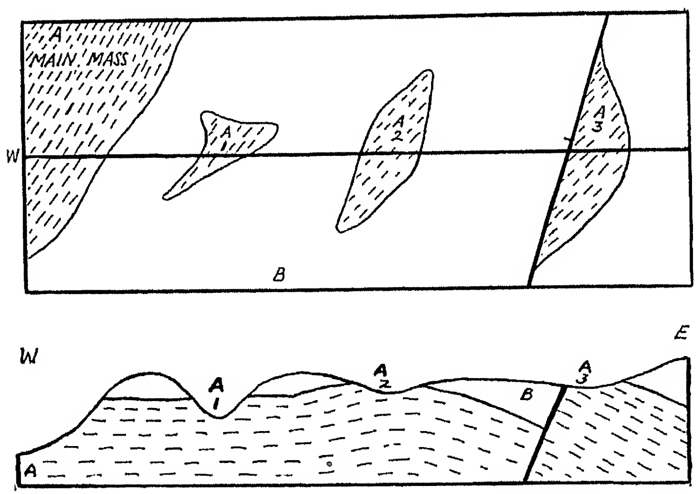

FIG. 79. Inliers.
Due to (1) erosion, (2) folding, (3) faulting.

In other cases erosion has been aided by an anticlinal fold, as in the Peasmarsh inlier near Guildford and the inliers of Chalk in Eocene beds at Windsor and Chislehurst (Sheets 285, 269, 271). Again, faulting may play a part in the formation of inliers.

3. OUTLIERS

An outcrop of younger beds surrounded by older is an outlier. An example is the hill of Lower Chalk, isolated by erosion from the Chiltern escarpment, near Cheddington, on the line between Tring and Leighton Buzzard; and another is Croham Hurst, near Croydon, a hill of Eocene

beds surrounded by Chalk. A synclinal fold may account for the preservation of some outliers, such as the lines of Eocene outliers on the Chiltern dip-slope, and faulting is a factor in other cases.

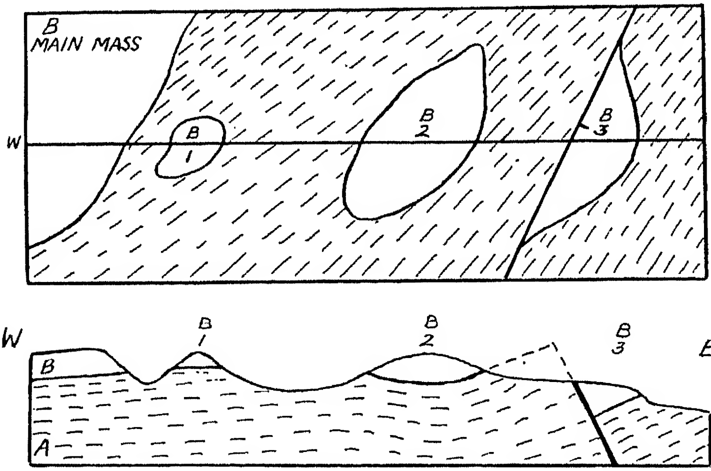

FIG. 80. Outliers.
Due to (1) erosion, (2) folding, (3) faulting.

4. WINDOWS AND KLIPPEN

Where an overthrust mass has been eroded so as to show an isolated patch of the beds below the thrust plane, the structure is called a window, or *fenêtre*, the French form. It looks like an inlier, but the beds within it are younger than those of the surrounding nappe. In the *fenêtre* of Verviers in Belgium Carboniferous Limestone is exposed beneath overthrust Devonian rocks.

Similarly an isolated portion of an overthrust mass, a nappe outlier, is called a *klippe* (German for a crag; plural *klippen*). It is not a true outlier since it consists of rocks older than those around it. Examples are the klippen of Chablais and the Northern Alps, and the remnants of gneiss of the Ben More nappe resting on Cambrian in the North-West Highlands of Scotland.

5. JOINTING

Most rocks are divided into blocks by cracks or joints, which generally follow a rather regular pattern. In igneous rocks they are due to contraction on cooling. The polygonal jointing of basalt runs at right angles to the cooling surface, and the columns are broken by other joints which may be

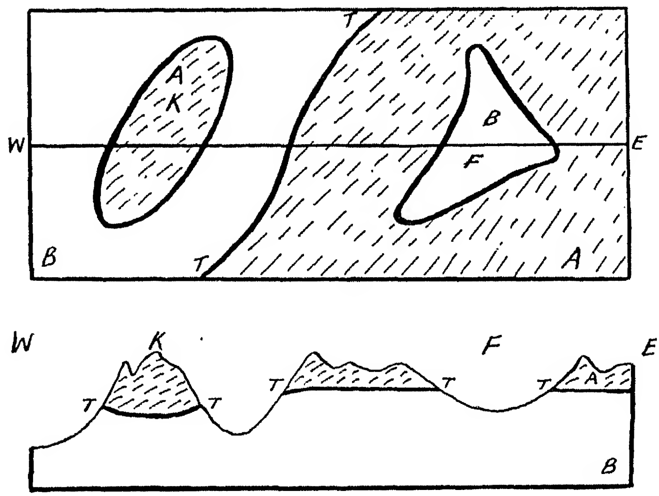

FIG. 81. Klippe and Window.
TT—Thrust.

convex or concave upwards. Columnar jointing is less perfect in the coarser-textured dolerites. Plutonic masses such as granites frequently show well-marked joints parallel to the upper surface of the intrusion, so-called bedding joints, and master joints and secondary joints cutting these.

The joints in sedimentary rocks have similarly been attributed to contraction on loss of moisture; but whereas true shrinkage cracks in starch or the mud on the floor of a dried-up pond are quite irregular, joints run in straight lines in two directions, as may be seen on the foreshore at Hunstanton. They are not due to contraction but to crustal stresses. In an anticline the higher beds are in a state of tension and

master joints develop parallel to the fold axis, with others caused perhaps by dome structure. The ancient rocks have undergone many crustal movements; and a weathered face of Pre-Cambrian rocks is often scarred and wrinkled in many directions.

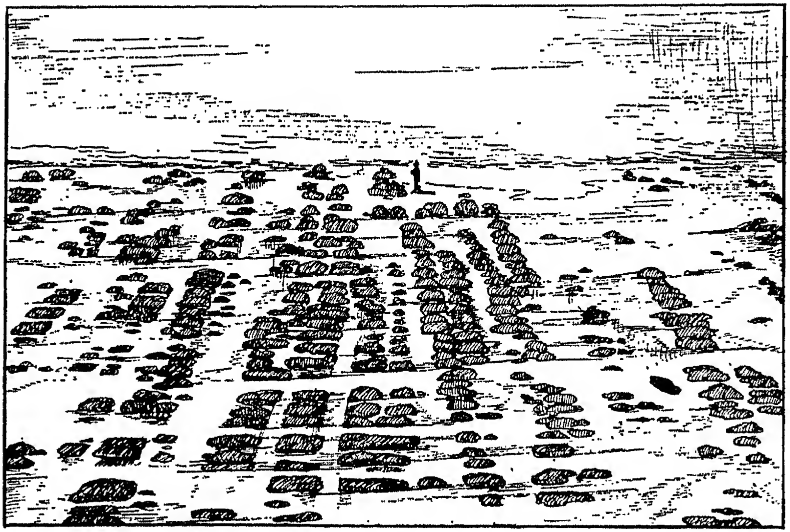

FIG. 82. Widened Joints in Lower Greensand, Hunstanton.

Other joints lie in the bedding planes, due to bands of marl or shale in limestone or to other changes in sedimentation. Films of mica in sandstone may cause planes of weakness and so produce the fissility of flagstones, but unless they cause actual breaks they are not joints.

CHAPTER XIII

MOUNTAINS

SOME mountains are accumulations of volcanic ash or lava, or both. Volcanic necks and extrusions like the domes of Auvergne form others, and salt domes are extrusions of a different nature. Other mountains are plutonic masses which, after crystallising beneath a cover of sedimentary rocks, have been exposed by denudation and now stand out above the

FIG. 83. Fault Block Mountains of the Great Basin, Western U.S.A.

FIG. 84. Section across the Western Jura. Anticlinal Ranges.

FIG. 85. Section across the Appalachian Mountains. Synclinal Ranges.

surrounding rocks by virtue of their superior resistance to erosion. For example, the Cuillin Hills of Skye are gabbro, Goat Fell in Arran is granite, and so are the Mourne Mountains in County Down.

There are also relict mountains, carved out of sheets of horizontal or gently tilted strata dissected by valleys and gradually reduced from plateaux to isolated blocks of hills. The heights of Saxon Switzerland are formed of well-jointed Cretaceous sandstone, and the buttes of Nebraska and the

kopjes of South Africa illustrate later stages in the erosion of horizontal strata.

But most mountain chains are due to crustal movements, faulting and folding. Fault mountains are seen in the Vosges and the Black Forest, on either side of the Rhine graben, and in the long parallel ranges of the Great Basin in the Western United States.

A simple type of folded mountains is seen in the Western Jura, where the anticlines form ridges and the synclines valleys. More commonly there is inversion of relief, as in the Appalachians of Pennsylvania, which are synclinal chains with valleys eroded along the anticlines. It is clear

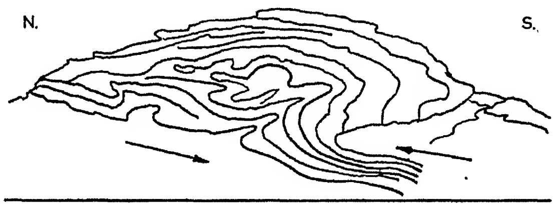

FIG. 86. Structure of the Swiss Alps, diagrammatic.

that folded mountain chains are due to tangential pressure resulting in reduction of area. They have moved in response to orogenic (mountain-forming) forces, in contrast to the radial up or down faulting due to epeirogenic (continent- or plateau-building) forces. Crust movements of both types are included in the term diastrophism (=distortion).

The Alps have a very complex structure, and they have been studied in great detail. Here the compression is of the order of 1,000 miles, and it appears that a series of gigantic overfolds and overthrusts have piled nappe upon nappe. Rocks of the same age but different facies, of shallow and deep water origin, now lie in close proximity owing to thrusts from the south.

The theatre of mountain building of the Alpine type is known as an orogen; and the drama is in three acts. First comes petrogenesis, the deposition of a thick series of rocks in a geosyncline. This may extend over more than one

geological Period. Next there is orogenesis, the crumpling and uplifting of those deposits as one flank of the geosyncline is forced toward the other. This movement, apart from minor precursors, has a relatively brief period of culmination; and it is followed by glyptogenesis, the sculpturing of the uplifted mountain mass by rivers, glaciers and the subaerial agents of erosion. There may, however, be some overlap, the early folding and denudation being followed by renewed deposition.

The rocks which now form much of the Alps were laid down during Mesozoic and early Cainozoic times in a great mediterranean sea called the Tethys, which separated Europe and Asia from the southern continent of Gondwanaland, including Africa, peninsular India and Australia. Shallow epicontinental seas from time to time flooded parts of these land masses, giving discontinuous deposits, in contrast to the unbroken succession formed on the subsiding floor of the geosyncline. But incipient lateral pressure raised the floor of the Tethys in places, forming islands and land masses. Then in Middle Cainozoic times came the irresistible northward drive of Africa, pushing the relatively weak deposits of the Tethys in overfolds and overthrusts on to Europe. Subsequent erosion has removed thousands of feet of rock and sculptured the deep valleys and lofty summits that we see in the Alps to-day.

The old idea that mountains are due to contraction of a cooling earth beneath a solid crust, like a wilting apple, does not meet the case; for the wrinkles on the skin of an apple are formed continuously and cover the whole surface, but mountain formation is sharply delimited in time and in space.

It was suggested by T. Mellard Reade that the deposits in the lowest part of a geosyncline were at such a depth that heat caused them to expand and pucker; but such expansion is quite inadequate to account for any mountain chain. Joly regarded mountain building as part of the normal cycle of events due to the accumulation of heat of radioactive origin. This heat, he estimated, was sufficient to fuse the basaltic substratum (part of the sima) at intervals of thirty million

years. The basalt expanded on fusion and its density was reduced. The continents therefore sank deeper, just as a ship sinks deeper in fresh water than in the ocean, and the seas transgressed over their flanks. The surface was in a state of tension and there was much volcanic activity and intrusion of dykes and other bodies of magma. When the basalt again became solid, through convection currents or other losses of heat, it contracted; the continents floated higher, shedding the seas; and the surface, now too big for the substratum, was crumpled into mountain chains. This theory of Joly's would be more tenable if there were any evidence of orogenic movements occurring in cycles of thirty million years or any other period.

There are indeed certain orocratic periods, when mountain building took place. To the Middle Cainozoic we assign the Alps, Pyrenees, Carpathians, Caucasus, Himalayas, Andes and Rocky Mountains, indeed all the really high mountain chains of to-day. But we can also trace the denuded roots of ancient mountains. Their date is clearly subsequent to the latest rocks involved in their structure and earlier than the oldest deposits resting unconformably across their folds. In the British area the Alpine storm produced only such minor ripples as the Weald and the London and Hampshire Basins, stretching east and west, with vertical Chalk in parts of the Isle of Wight and Dorset and with Eocene and Oligocene beds also involved in the movement. It succeeded a long period of quiescence, ever since the Armorican or Hercynian folding of Carbo-Permian date. This also gave east-west folds, well seen in S.W. Ireland, the Devon synclinorium, the South Wales coalfield and the Mendip Hills. They are covered unconformably by Mesozoic rocks but continue by the Kent coalfield and Northern France to the Ardennes. The Bristol coalfield shows both east-west and north-south folding, and farther north important faults with N.-S. strike are seen in the Malvern Hills and elsewhere.

Earlier still, the Caledonian mountain chains were formed at the end of Silurian times, with a N.E.-S.W. strike which is well seen in Glen More, the Highland Boundary fault, and the Southern Uplands of Scotland, and also in Northern

Ireland. The Pre-Cambrian rocks of Charnwood Forest have a N.W.-S.E. strike.

It sometimes happens that folding may be renewed at a much later date by posthumous movements. But on the other hand folded rocks are far stronger than unfolded ones, just as corrugated iron is stronger than sheet iron. These old mountain chains, though long since eroded to peneplains, have been re-etched and still dominate our hills, valleys and

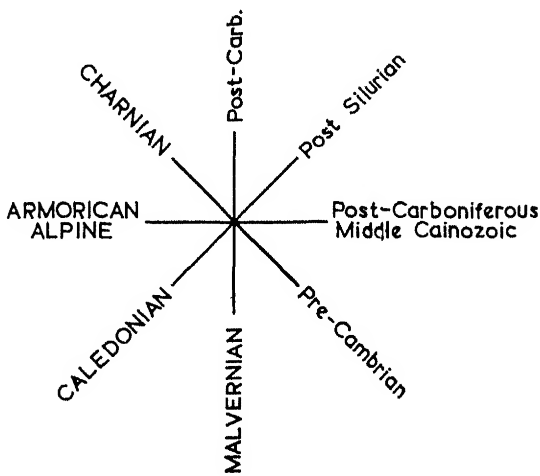

FIG. 87. Trends and Dates of the Principal Fold Systems in the British Isles.

coastlines. Their trends and approximate dates are shown in *Fig.* 87.

A plumb line set up near a mountain mass is deflected toward the mountains and does not point truly to the centre of the earth. Astronomical determinations of latitude are vitiated in consequence. Calculations of the effect of the known mass of the Himalayas and the Tibetan plateau in deflecting plumb lines at stations in the Indo-Gangetic plain gave results considerably greater than those actually observed : the mountains were not pulling their weight. Gravity determinations, too, show a defect of gravity in mountain

regions. The explanation seems to be that beneath the mountains there is a much greater thickness of low-density rocks, sial, than elsewhere. The mass of the mountains is compensated by this light-weight material, which has taken the place of the denser sima, so that a vertical column down to a certain level balances a similar column in any other region. The column is longer in the mountains, where the average density is low, shorter below the oceans, where the density of the rocks is high.

The sial indeed floats on the sima as an iceberg floats in the sea. The plains are like thin sheets of ice, of shallow draught,

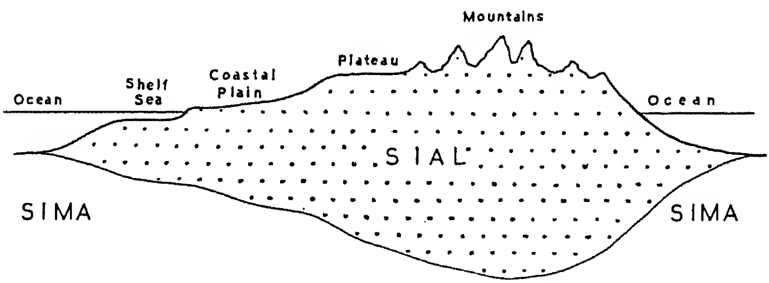

FIG. 88. Diagrammatic Section to illustrate Compensation.

while the mountains and plateaux are like lofty icebergs of greater draught. This does not mean that Mount Everest has a deep excrescence of sial beneath it, but the Himalayas as a whole are buoyed up by a great thickness of sial, while the sial is much thinner beneath the Indian plains and absent or extremely thin under the oceans.

Compensation of a mountain mass by the lower density of its roots may or may not be complete. It is continually being upset by denudation, which unloads the highlands and deposits material on the sea floors. The former areas tend to rise in consequence and the latter to sink, and this adjustment to change of load is known as isostasy (=equal standing). It accounts for part, but only a part, of the rise of mountains and the sinking of basins of deposition. The ice caps that in Pleistocene times covered much of northern Europe

and America caused the areas beneath them to sink; and since the melting of the ice these areas have risen and some of them are still rising.

The distribution of sial and sima also indicates that continents can never be depressed to form ocean deeps. Only shallow seas may spread over them. Nor can ocean deeps be elevated into continents. Yet there is clear evidence that the continental masses have not always occupied their present positions. Throughout Palæozoic times the British Isles received sediments from land to the west; and common faunas often indicate shallow-water connections between Britain and eastern North America. The western and eastern coasts of the Atlantic fit into each other, and rocks and structures in

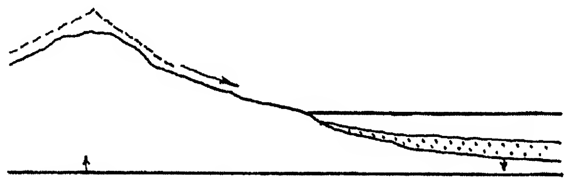

FIG. 89. Isostatic Adjustment to Erosion and Deposition.

South America correspond closely with those of Africa. It looks, as Wegener contended, as if America has drifted away from the Old World. Again, the *Glossopteris* flora of Carboniferous and Permian times links Australia with India, Africa and South America, which seem at that time to have formed one continental mass, the ancient Gondwanaland, but have since drifted apart. The northward drive of Africa in the Alpine orogeny has already been described. The forces that could cause continental drift have not yet been satisfactorily explained, but the theory is certainly preferable to the alternative idea of the foundering of continents.

A theory favoured by Holmes is that heat of radioactive origin induces slow convection currents beneath the crust. Rising below the continents, which have a blanketing effect, they flow outward and tend to disrupt the sial masses. Descending in cooler regions, they drag down the sial with

them, causing geosynclines; but when the downward currents cease to flow the roots of sial buoy up the geosynclines, which are elevated and compressed to form mountains.

Compensation, isostasy and continental drift suggest that the solid rocks must have some of the properties of viscous fluids. Yet the study of seismic waves shows that they are more rigid than steel. These two apparently contradictory views are not really incompatible. To the quick changes of stress produced by earthquakes or by tides rocks oppose a very high rigidity; but they yield slowly to long-continued forces. The equatorial bulge is evidence of this. A stick of

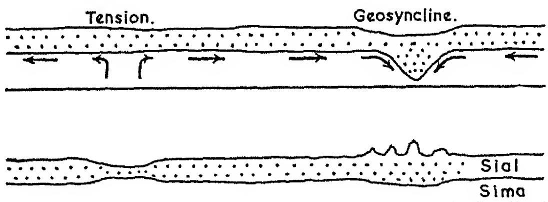

FIG. 90. Subcrustal Currents and their Effects.

sealing wax is a familiar brittle solid; it will snap rather than bend; but if it is fixed at one end in a horizontal position it will be found in a few months to have sagged slowly under its own weight.

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CHAPTER XIV

SECTION DRAWING

A GEOLOGICAL map is not merely a two-dimensional plan of the areas where certain kinds of rock crop out. To the geologist it indicates how the beds lie below the surface, what folding and faulting they have undergone, where unconformities occur, and indeed much of the geological history of the country represented on the map. But some practice is necessary before the student can correctly read a map in four dimensions—length, breadth, depth and time—and sections must be drawn across a number of maps showing a variety of rocks and structures. Such sections (there is one at the foot of each modern sheet of the 1 inch to 1 mile map of the Geological Survey of England and Wales) are known as horizontal sections because, although they represent vertical cuts across the area, their length is many times greater than their height. Vertical sections, on the other hand, are used to show the strata penetrated in a shaft or boring.

Unless the scale of the map is large, or the area is mountainous, it will be necessary to exaggerate the vertical scale of the section. With a 1-inch map a scale of 3 inches to the mile may be used for heights, or even 6 inches to the mile in very flat country or where the beds are thin. Some distortion will result, especially where beds pass from the horizontal to the vertical and their thickness appears to be reduced to one-third owing to the different scale. The very convenient profile sheets supplied by Messrs. T. Murby and Co. are ruled with lines at intervals representing 100 feet on the scale of 6 inches to the mile; but these may be used as 200-foot intervals to give an exaggeration of three times the horizontal. If graph paper is used, with 0.1 inch representing 100 or 200 feet, the magnification is 5.28 or 2.64 times the horizontal scale.

In selecting a suitable section line, choose one cutting the outcrops, not running along them. Rule a pencil line passing through as many outcrops as possible, through any inliers or outliers, and cutting faults, in order to get the clearest view of the structure. The edge of the map is not a good line to choose because, unless the adjacent sheet is at hand, half the evidence is missing.

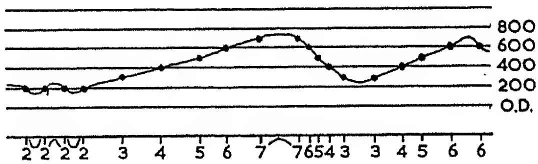

FIG. 91. Drawing Surface Line on Profile Sheet.

Having marked the line of section, lay the edge of a piece of paper (a strip of foolscap is suitable) along the line and mark on it the position of every contour that crosses the section line. If the same contour is crossed several times in succession, lower ground may be marked ᵕ and higher ground ⁀. These symbols may also be used to mark the lowest points of valleys (streams, or Alluvium) and the highest points of

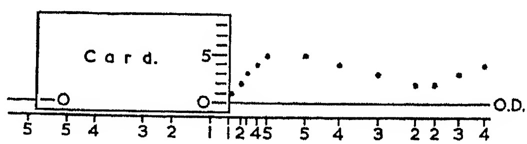

FIG. 92. Drawing Surface Line without Profile Sheet.

hills (trigonometrical stations, Plateau Gravel, etc.). Any spot heights near the section line should be noted, as well as contours that approach it.

Then place the strip of paper along one of the lines of the profile sheet, not the bottom but about one-third up. This line is marked as Ordnance Datum. Vertically above the point where the 100-foot contour crosses the section line put a dot midway between the O.D. line and the next. The 200-

foot contour will have a dot on the first line above O.D., the 400 on the second, and so on. If profile sheets are not used it is a good plan to copy the scale of 3 inches to a mile, given with the section at the bottom of most modern one-inch sheets of the Geological Survey, on the edge of a piece of thin card and use that in placing the dots. When all the contours and spot heights have been marked, draw a line through them to represent the surface of the ground. This surface line should not be inked in before the section is completed, for it may be necessary to modify it to fit the geological outcrops.

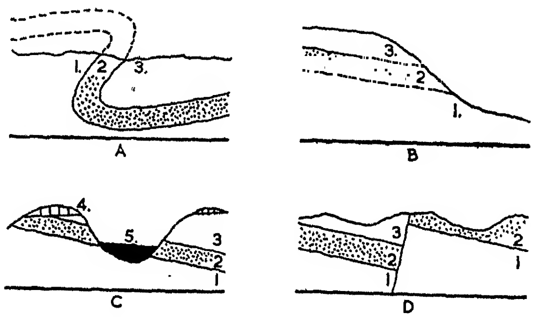

FIG. 93. Cases where Beds dip away from the younger rock.

Geological boundary lines are transferred to the section in the same way as the contours. If the same boundary is cut more than once, the line joining its points of outcrop will give the dip, if the surface line can be trusted and the dip is constant. Dip arrows are not numerous on most maps, and few of them give the angle of dip as well as its direction. If this angle is given it must be increased in the section in accordance with the exaggerated vertical scale used.

In general, the older beds dip toward the younger, unless the beds are inverted or the ground slopes in the same direction as the dip and at a steeper angle. If the boundary marks an unconformity, or a fault, the dip is not necessarily toward the younger rock.

The angle of dip can be found by trial and error. If a bed appears too thick in the section, according to the column at the side of the map, the dip must be reduced; if it is too thin, the dip must be made steeper.

Alternatively, if the top of a flat-lying bed 400 feet thick crops out at a point, its base will be about 400 feet below that point. Put a dot there and join it to the point where the base of the bed crops out.

On the older maps there is no column drawn to scale but only a series of tablets to explain the colours used on the map. The approximate thickness must then be judged from experience and knowledge of stratigraphy, or by drawing a trial section through a point where the angle of dip is indicated.

FIG. 94. Dip found by joining points of Outcrop.

FIG. 95. Dip found from known thickness of bed.

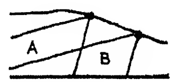

FIG. 96. Dip found by Trial and Error.

In hilly country strike lines or stratum-contours may be drawn through points where a geological boundary cuts the same contour on either side of a ridge. The distance between them will give the dip, as in Chapter IX.

Any curvature of outcrops must be noted. If not due to a hill or valley it probably indicates a fold, and the fold axis should be shown even if the outcrops along the line of section are not affected. If the outcrops in one limb of a fold are markedly narrower than in the other, this is probably due to a steeper dip on that side.

In sections across low-lying districts the geological structure may be shown to 500 feet below O.D. If a deep boring occurs on or near the line of section, the thickness of all the beds it cuts should be shown at that point only.

The following are among the common errors that most beginners make. (1) The ruler is used to give neat, straight lines, though the dip may vary from point to point. The use

of problem maps, with their unnatural geometrical construction, may be partly to blame for this. (2) The upper and lower boundaries of a bed are not kept parallel as they should normally be. (3) All beds are given the same dip, irrespective of any unconformities. In particular, Drift deposits, such as Alluvium, Gravel and Clay-with-flints, are made to dip conformably with the solid rocks instead of lying unconformably above them. (4) Small outliers are represented in sharp synclines instead of by raising the surface line, and valley inliers are given non-existent anticlines.

When the geological boundaries and the surface line have been brought into satisfactory accord they should be inked

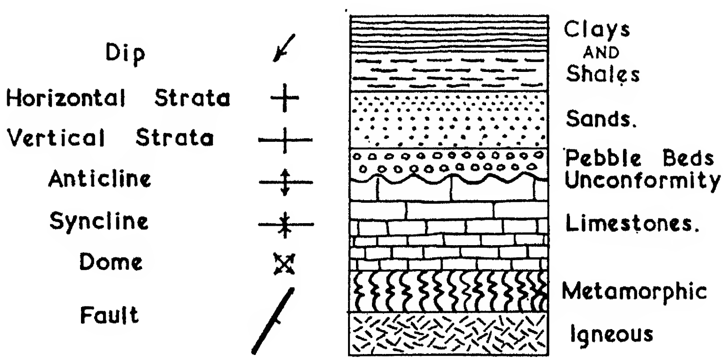

FIG. 97. Symbols used on Geological Maps and Sections.

in with a fine pen and Indian ink. The beds may be given a thin wash of water colour. Crayons are clumsy, opaque, and better avoided. The transparent water colours sold in books by photographic dealers for tinting prints and lantern slides are very convenient. The names of the beds may be written below the section if there is room; or they may be marked by their symbols (g^{12} for Kimmeridge Clay, h^3 for Gault, and so on), and the symbols explained below the section. The names of towns, rivers and hills along the line of section should be shown. In all cases the orientation of the section must be indicated and the name and number of the map must be noted. These will be found in large type in the

top centre and top right corner of the sheet, and must not be confused with the small name and number close to the top margin, which refer to the next sheet to the north. The student should not be satisfied with his efforts until they approximate closely to the section given at the bottom of the map.

It may be that more than one section is needed to show the structure of the area represented on the map. It is necessary, too, to practise describing the whole of the area, giving a brief account of its geological history. Begin with the sequence of deposits, pointing out any gaps and unconformities. Describe the nature of the folding, faulting and intrusions, and with their date if possible (*e.g.*, post-Carboniferous and pre-Triassic). Then the river system should be described, in relation to the structure, with mention of erosion features such as outliers.

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CHAPTER XV

UNDERGROUND WATER AND SPRINGS

Of the rain that falls on any area only a fraction sinks through the soil to augment the underground water supply. The proportion varies in different districts, depending on the annual rainfall and its distribution, temperature, slope of the ground, vegetation and the type of soil and underlying rocks. In England, with an average annual rainfall of 30 inches, 5 inches may run off into streams and rivers and 18 inches may be lost by evaporation, leaving only about 7 inches on the average to percolate down to the natural reservoir underground. This is equivalent to 102 million gallons per square mile.

Water passes through the rocks in two ways: by means of the pore space, as in sand and gravel, in a manner familiar to any child on the seashore; and through joints, fissures and caverns, as in granite or limestone. Even the most compact rocks contain some quarry water. The ease of transmission therefore depends on the texture and the fissuring of the rocks, those with high pore space or frequent joints transmitting water more readily than compact unjointed ones. But pore spaces that are sealed off from one another do not increase the permeability of a rock.

The pore space is greatest when the particles in the rock are nearly uniform in size. With closely-packed spheres of uniform size the pore space can be shown to be independent of the diameter; but the smaller the diameter the greater will be the effect of capillary attraction. In ill-graded deposits small particles get in between the larger ones; and cementation may further reduce the permeability. Quicksands or running sands are so full of water that they have lost their coherence.

Clays are highly impermeable; they absorb much water but retain it by surface tension. Fine sands and loamy sands

are partially permeable. But even clays in time of drought become fissured to a depth of several feet and may then admit water to underlying permeable beds. Oolitic limestones are often highly porous and also well jointed.

The rate of flow of water in river gravels, with a gradient of 100 feet in a mile, has been estimated at 2½ to 63 miles *per annum;* but in fine sand with a slope of 10 feet in a mile it is as low as 52 feet a year. A well at Grenelle in Paris, nearly 1,800 feet deep, draws its water from the Lower Greensand which crops out 100 miles to the eastward. It must take many years for rain falling on the outcrop to reach the Grenelle well.

The flow of water through joints and fissures depends on their frequency and width. They may be widened by anticlinal folding, or by the yielding of soft underlying beds, or by solution, as in limestones.

The water passes down through unsaturated rocks till it reaches the saturation level. This plane of saturation or water table is usually highest under the highest part of the outcrop of a permeable bed, where the greatest rainfall occurs, and it slopes at varying angles down to the valleys where springs break out. It is far from being a true plane, but has a convex surface owing to the resistance and slow rate of flow. It separates the unsaturated, aerated, vadose zone above from the saturated phreatic zone below. The ground water extends from the water table to a depth at which rock pressure closes all crevices, so that really deep mines are dry.

The Chalk is a good example of a thick water-bearing bed, or aquifer. The heavy rainfall over the North Downs and Chiltern Hills raises the water level there to 300 or 400 feet above Ordnance Datum, whence it falls to springs (1) along the Chalk escarpments, (2) along the junction of the Chalk and Eocene beds, and (3) in the valleys that trench the dip slopes. An example of the first group, escarpment springs, feeds the Silent Pool at Albury, where the flow is increased by a fault. In some places the Chalk Marl is the impermeable bed holding up the water, in others the Gault. The springs at Chadwell and Amwell, supplying the New River, and at Beddington and Ewell in Surrey, mark the overflow

at the top of the Chalk; and those that feed the Colne, the Ver and the Lea are examples of springs in valleys running down the Chiltern dip slope.

The numerous springs along the Chalk-Eocene boundary between Croydon and Guildford attracted Saxon settlers who founded villages there; and to-day twenty parishes stretch across this boundary in a distance of 22 miles, a striking example of the influence of geology on population.

Many of the Chalk valleys are dry valleys: no streams flow in them though they were cut by streams. The water level has since fallen below the valley floors. The former high-water level has been attributed to a greater rainfall than at present,

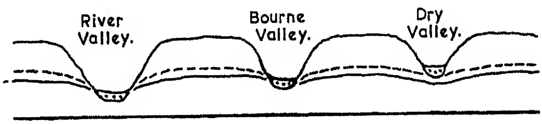

FIG. 98. Section through three Chalk Valleys. High water level, broken line. Low water level, continuous line.

or to the flood waters caused by the annual melting of the snow in the cold periods of the Pleistocene. But the principal factor is probably the cutting back of the Chalk escarpment (which has lowered the point of overflow in that direction), and also the lowering of the Eocene springs by erosion. This would reduce the whole water level in the Chalk and render the valleys streamless.

The water level in the Chalk fluctuates with the rainfall, and after long periods of drought many springs dry up. The Chiltern streams mentioned above then lose some miles of their headwaters and their valleys, to that extent, go dry. The River Mole in the Mickleham Valley is often dry in summer time, the water from the Weald flowing through swallow holes into the Chalk and reappearing near Leatherhead.

Conversely, after prolonged heavy rainfall, a normally dry valley may have a stream flowing in it, because the water

level then rises to the floor of the valley. These intermittent streams, known in different localities as bournes, winter-bournes, nailbournes, lavants and gypsies, may flow for some weeks in several successive years, and then fail for many years. The West Wickham bourne, in West Kent, was not seen for 33 years, and it was thought that the pumping station at Kent Gate had permanently stopped it. In the Caterham Valley a row of houses was built across the course of the Croydon bourne. Heavy winter rainfall sends up the water level in the Chalk until it reaches a valley floor. Water then appears and flows down the valley as far as the Chalk is saturated, beyond which point it begins to disappear; but

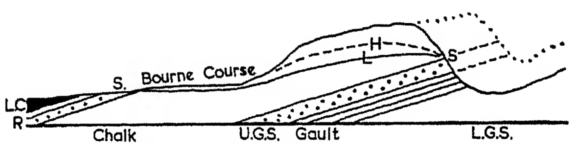

FIG. 99. Section along the Valley of a Bourne. H—High water level. L—Low water level. S—Spring. LC—London Clay. R—Reading Beds, etc. UGS—Upper Greensand. LGS—Lower Greensand.

as the underground flood increases the bourne rises higher up the valley and flows farther down it, often joining a permanent stream. By gauging the height of water in a number of wells, Baldwin Latham was able to predict the date of outbreak of the Croydon bourne and its approximate volume.

Before their origin was understood the rising of bournes was regarded as ominous, predicting pestilence (often correctly), famine, war, or a change in the British Constitution. Hence such terms as the Hertfordshire Womere and Croydon's Woe Water. Scarcely more reasonable was the syphon theory of their origin, which postulated an immense reservoir taking several years to fill and emptying automatically when the water reached the highest part of the outlet pipe. The outlet would have to be airtight, like a tube, while the reservoir was under atmospheric pressure; and a reservoir of

gigantic proportions would be required. The Chalk does not contain great caverns as many limestones do.

Above the Chalk, water passes freely through the Thanet Sand and sandy Reading Beds but is checked by the Woolwich and Reading loams and the thick mass of the London Clay. When wells were first sunk through this into the Chalk, water rose in them, in some cases to the surface of the ground, owing to the head of water in the Chalk outcrops. But pumping from the numerous wells of London has lowered the water level to 200 or 300 feet below Ordnance Datum. Though it continues to overflow at the margins, the reservoir in the Chalk below London is being emptied faster than water can flow in to replenish it.

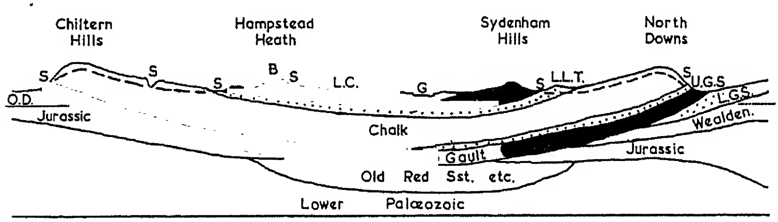

FIG. 100. Generalised Section across London's former Artesian Basin. G—Gravel. B—Bagshot Sand. LC—London Clay. LLT—Lower London Tertiaries. UGS—Upper Greensand. LGS—Lower Greensand. S—Springs. O.D.—Ordnance Datum.

Pumping lowers the water surface in an inverted cone about a well, and where many wells are extracting water these cones of depression coalesce and there is a general lowering of the water level. There was considerable recovery in the water level below London after the destruction of 1940-41 had put a stop to pumping at many bombed premises; but if pumping continues at the former rate it will not be long before the Upper Chalk is dry under London. East of London, where the River Gravels rest directly on Thanet Sand and Chalk, water formerly issued as springs; but the water gradient is now reversed and brackish river water enters the Chalk and causes increasing salinity in the water pumped from wells in Greenwich, Barking and Grays,

Gravels gave London and many neighbouring villages their first water supply, from shallow wells and springs that broke out where gravel water escaped over the London Clay. Springs at the base of the Bagshot Sands of Hampstead Heath feed the Fleet (Holebourne), the Tybourne and the Westbourne, streams now bricked over as sewers.

Below the Chalk and Gault the Lower Greensand gives a good supply of water under great hydrostatic pressure in the neighbourhood of Slough; but it is absent beneath London.

The chief water-bearing beds in the Jurassic System are the Great Oolite Series, yielding strong springs near Bath; the Inferior Oolite and Midford Sands; the Lincolnshire

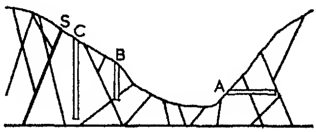

FIG. 101. Water Supply in Jointed Crystalline Rocks. A—Adit. B—Flowing well. C—Dry well. S—Spring.

Limestone, supplying Peterborough and the Fenland with potable water; and the Northampton Sands.

The Triassic and Permian sandstones, and particularly the Bunter Pebble Beds, yield abundant water, but it is often hard, owing to calcium sulphate, and sometimes saline, especially at depth.

The sandstones in the Coal Measures, Millstone Grit and Old Red Sandstone are more compact than those of Mesozoic age, and they are more folded and faulted. Their water supply depends chiefly on joints and faults, and also on the extent of their gathering grounds. A thin grit band between shales is not likely to give a large supply of water. In the Carboniferous Limestone joints and bedding planes, widened by solution, may yield great quantities of water. Caverns and underground streams occur. Surface streams disappear down swallow holes and re-emerge, like the Aire

at the foot of Malham Cove, in what are sometimes called Vauclusian springs, from a locality in the South of France.

In metamorphic and plutonic rocks water circulates along the joints, and a well will not yield a supply unless it cuts water-bearing fissures. Water may flow over the top of a well, like a spring, if the joint system connects with a gathering ground at a higher elevation. An adit driven into the side of a valley is often more successful in cutting fissures than a well.

Where a permeable bed dips beneath an impermeable one, the water is held down by the cover and the hydrostatic pressure increases with depth. This is an artesian slope. In wells sunk through the cover the water rises to a height

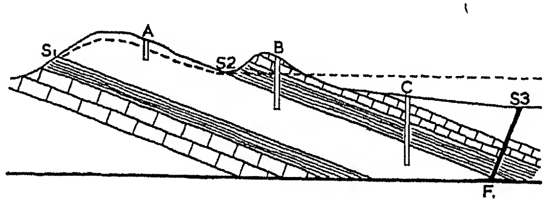

FIG. 102. An Artesian Slope.
A, B, C—Wells. F—Fault. S_1, S_2, S_3—Springs.

governed by the pressure, which itself depends on the free water table at the outcrop of the permeable bed. If it spouts up above the ground the well is an artesian one (named from Artois, Pas-de-Calais); if it fails to reach the surface it is sub-artesian. The Bunter Sandstones dipping beneath the Keuper Marls in Nottinghamshire, and the Lower Greensand beneath the Gault in Cambridgeshire, furnish good examples of artesian slopes. A fault or other weakness in the cover may give rise to artesian springs or blow-holes. If the dipping beds rise again in the form of a syncline an artesian basin is formed. The London Basin was an example of this before over-pumping lowered the water level; and west of London the Lower Greensand yields an artesian supply around Slough.

A perched water level is one that is held up above the normal level and has unsaturated strata below it. A mere

marl band in the Chalk may have this effect, holding up a small supply at an unexpectedly high level, which may, however, disappear if a well is carried through the impermeable band. Along the Eocene escarpment of East Surrey and West Kent there is a perched water level in the Blackheath

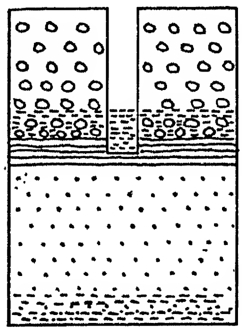

FIG. 103. A Perched Water Level.

Pebble Beds, and water from it flows down over the Woolwich loams to disappear through the Thanet Sand and join the water in the Chalk.

Besides meteoric water, derived from rain and snow, strata may contain connate water which was enclosed at the time

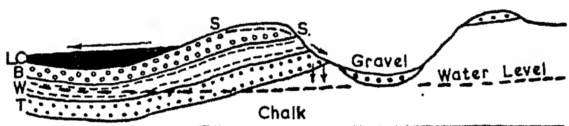

FIG. 104.—Perched Water Level at West Wickham, Kent.
LC—London Clay. B—Blackheath Beds. W—Woolwich Loams, etc. T—Thanet Sand.

they were formed. The brackish water in the Old Red Sandstone may be such fossil water. Another type, known as magmatic, plutonic, intratelluric or juvenile water, is derived from igneous magmas and is making its first appearance at the surface of the earth. Hot springs and geysers are

examples of this, and so perhaps are the warm waters of Bath.

Some waters contain soluble salts in notable quantity and have in consequence some curative value. Numbers of mineral springs achieved great popularity at one time but are now almost forgotten. Those at Bath and Harrogate are still much used.

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CHAPTER XVI

RIVERS

A TYPICAL river, such as the Amazon, the Ganges or the Po, is formed by the union of many mountain torrents, flows rapidly with a steep gradient through the hilly country, and, on reaching the plains, meanders with a slow current to the sea. Exceptionally there may be no mountain tract, as in the Mississippi, or no coastal plains, as in the rivers of Norway.

The importance of rivers is manifold. They are essential links in the circulation of water from sea to land and back again, on which all life on land depends; they erode their channels, cutting gorges; they carry away the products of subaerial erosion which would otherwise accumulate and form a protective cover; and they throw down deposits of gravel, sand or mud wherever their current is checked.

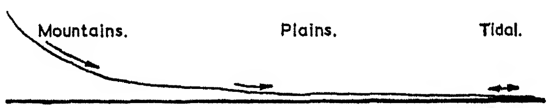

FIG. 105. Mature River Profile.

The velocity of a river varies at different parts of its course and also at different parts of its cross section. Friction with the bottom and sides holds back the water there, and the current is swiftest in midstream; for which reason boats working upstream generally hug the banks and leave the centre to down-river traffic. Wind and tide may also affect the current, and eddies occur in all but the straightest and most smooth-bottomed streams.

The profile of a mature river approximates to a logarithmic curve of the type expressed by the equation:

$$y = a - k \log (p - x),$$

where y=height in feet of a point above sea level, x=its

distance in miles from the mouth, p=length in miles of the river, and a and k are constants. But the simple curve is often broken, owing to the immaturity of the river, to the outcrop of more resistant rock, or to renewed downcutting by the river due to uplift or other causes. A youthful river is vigorously attacking these irregularities; in maturity it has reduced them to base level and erosion is very slow. The breaks in the curve are called knick-points, from a German word meaning a break or flaw (not nick).

The transporting power of a river depends on the volume and velocity of the current and on the size, shape and specific gravity of the materials carried. If a stream that can just

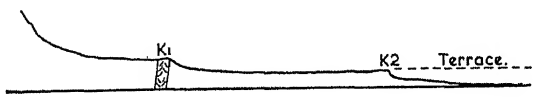

FIG. 106. River Profile showing two Knick-points. K_1—Due to igneous rock. K_2—Due to rejuvenation.

move pebbles of one ounce weight has its velocity doubled in time of flood, it can then shift stones weighing four pounds, for the transporting power varies approximately as the sixth power of the velocity, and $2^6=64$ ounces. The boulders seen in the beds of mountain streams in summer are clearly beyond the power of such streams to move; but a thunderstorm in the hills may transform a trickle into a powerful torrent which transports much material downstream and then strands it until the next spate.

Round stones are more easily moved than angular ones; and the effective weights are reduced by immersion in water. A 5-ounce pebble of quartzite only weighs about 3 ounces in water.

Ice may help in river transport by freezing around stones and floating them up, and also by forming ice-dams which hold up water and release it in a flood when the dam bursts. This often occurs in the rivers of Northern Russia, where the thaw comes to the upper reaches while the lower parts are still frozen.

The amount transported by a big river may be judged from figures relating to the Mississippi, which carries out to sea every year some 400,000,000 tons in suspension, 120,000,000 in solution, and 40,000,000 rolled along the bottom, a total of 560,000,000 tons. This is equivalent to a lowering of the whole area drained by the Mississippi by one foot in 4,000 years. The Ganges is more efficient, owing to its mountainous source and to heavy seasonal rains, and lowers its drainage area one foot in 1,750 years.

Erosion of its channel by a river is often termed corrasion. Clear water has little or no erosive power, except on rocks that are soluble in water. Thus at Aber Falls in Caernarvonshire the water has made little impression on the rock face over which it cascades, for it has filtered through a peat bog above the falls. But silt, sand, gravel and boulders are the river's tools: armed with them it forms a continuous belt of abrasive material wearing away its channel. These tools are provided partly by the river itself, partly by the sub-aerial agents of erosion such as rain, frost and wind. The talus that accumulates on steep hill slopes and the alluvial cones beneath rain gullies supply much of the necessary material.

Not only is the river channel worn away, but the fragments themselves have their edges rounded, and after long transport may become almost spherical if they are not very hard. Daubrée made the experiment of enclosing fragments of felspar in a revolving cylinder. After 192 hours, equivalent to a journey of 287 miles, it was found that the felspar had been reduced to mud and a good deal of potash had gone into solution.

Here too velocity is important. With the same tools the erosive power of a river varies roughly as the square of the velocity, for when the velocity is doubled twice as many particles strike a given area per minute, and with doubled momentum. But the tools themselves will be very much weightier and more effective, since the transporting power is now about 2^6 times as great.

The most spectacular irregularities in profile are seen in waterfalls and rapids. Niagara is a classic example of a com-

mon type of waterfall, in which a resistant cap rock is underlain by more easily eroded beds. Here the Lockport Dolomite (Niagara Limestone) is the cap rock; it forms an escarp-

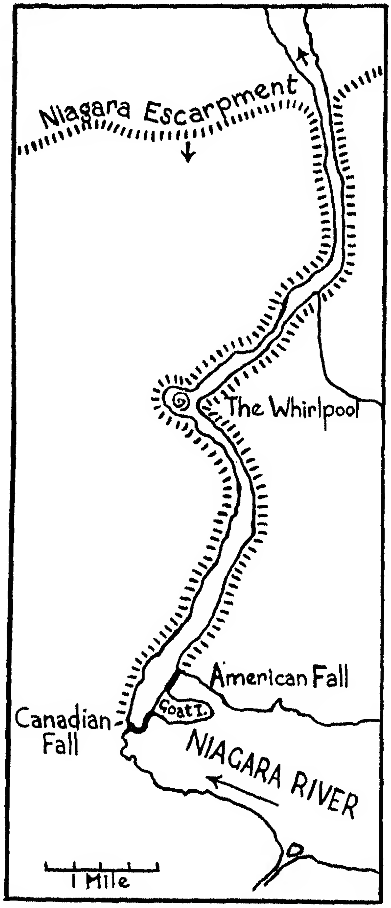

FIG. 107. Map of Niagara Falls and Gorge.

ment seven miles north of the present falls, and at one time the river fell over this escarpment with a drop of 300 feet instead of the present 160 feet. Plunging over the limestone the river easily erodes the shales and sandstones beneath it;

the limestone is undercut and in time crashes into the whirlpool below, providing fresh tools for its own destruction.

Thus the falls move upstream, and down the dip, diminishing in height and leaving a narrow gorge which rain and frost have not had time to widen appreciably. The Canadian Falls, which carry 95 *per cent.* of the water, are receding at the rate of 4 or 5 feet a year, while the American Falls are practically stationary. The rate was probably greater in

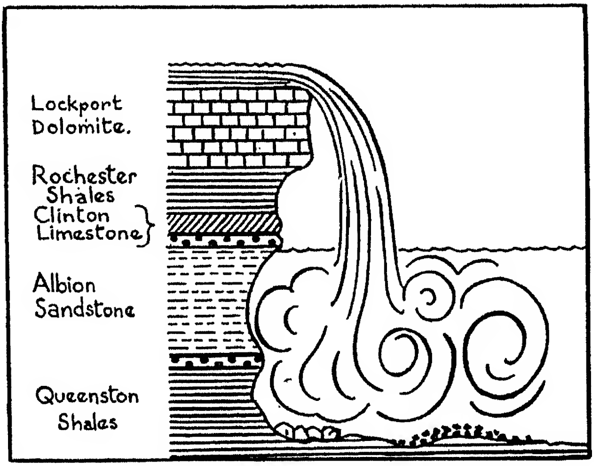

FIG. 108. Section through Niagara Falls.

the narrow gorge than it is now, when the falls are 4,000 feet wide; but taking it at 5 feet a year we have only 7,000 years as the time required for the recession of seven miles from the escarpment and the loss of nearly half the original height. Such waterfalls are very transient affairs.

Where the volume of falling water is small the churning action below it has little effect. Spray helps to erode the weak underlying rocks, and the cap rock is left overhanging for some distance on either side of the waterfall. This is seen in many of the Yorkshire "forces." The valley below the fall is not in this case a purely river-cut gorge. Exceptionally, erosion is more rapid on either side of the fall, which pro-

tects the rocks behind it from frost action and from alternate wetting and drying, so that they stand out like a bastion.

Lava flows, as in the Victoria Falls, form the cap rock in many cases, and sills in others. A vertical dyke or a plutonic intrusion may cause a waterfall that does not recede up-stream, or more commonly a succession of rapids. Corrasion in such rocks is very slow and the valley above may reach a mature stage of development before this irregularity is removed from the profile.

Discordant junction is the cause of many waterfalls. In glaciated regions the main valleys have been overdeepened and the side valleys left hanging, their streams falling to the floor of the main valley. The Aare valley between Brienz and Meiringen has many such hanging valleys and falls, of which the Reichenbach Fall is the best known. Discordant junction with the sea causes cliff waterfalls, as in many streamlets on the coast of Dorset and the Isle of Wight. A recent fault-scarp too may cause temporary waterfalls.

Eddies in a rocky gorge swirl stones round in circles and drill cylindrical holes. The stones are rounded and worn away, only to be replaced by others. These pot-holes, as they are called, may be seen in many rocky stream beds and often in places where the water no longer flows.

It must always be remembered that river erosion is confined to the actual river bed. The most youthful and energetic of rivers is bedridden, though the bed may not be a fixture. A river can only excavate a steep-sided gorge, and afterwards carry away the loose material produced by sub-aerial erosion, which alone can widen the gorge into an open valley.

In the hills a river generally follows a fairly straight course, the line of steepest descent, though even here in times of low water the stream is easily deflected by stones and forms little meanders. In the plains, where the gradient is low and downcutting has ceased, a river meanders in wide sweeps. Its momentum carries it on, once it has deviated from its normal course, until gravity swings it back, when again momentum carries it across to the other side of the

valley. The amplitude of the meanders depends on the volume of the river.

A glance at any meander in stream or river shows that the outer bank (cut bank) is steep and suffering erosion while on the inner side (slip-off slope) deposition may be going on. It has been stated that this is due to the greater velocity of the water on the outer side, as though the water had the rigidity of a line of Guards wheeling to the right or left. This is clearly not the case: the greatest velocity is still in mid-stream, but centrifugal force tends to pile up the water on

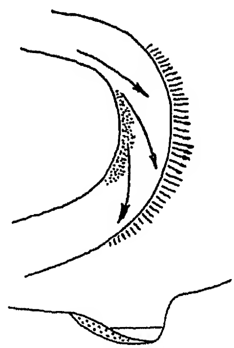

FIG. 109. A Meander in Plan and Section.

the outer side, whence there is a bottom current following a corkscrew-like course to the inside of the curve, which deposits sand or silt there. The water is shallow on the inside of the curve but deeper than the average near the outer bank; and so the middle of a curve is not a good place to ford a river. Before man interfered with it the Thames at London was cutting into the bank at what is now the Temple. The nearest ford was in the middle of the straight reach above this point, where Westminster Bridge now stands. Richmond Hill and the western face of Box Hill are river cliffs cut by the meandering Thames and Mole.

Owing to the constant erosion of the outer bank, meanders tend to increase in amplitude and to move downstream. They may multiply the distance between two points on a

river many times, the water returning after a lengthy circuit to a few hundred yards of its starting point. Then the river in flood is likely to cut across the narrow isthmus and erode a permanent short cut, leaving the meander silted at the ends and occupied for a time by what is called an ox-bow lake.

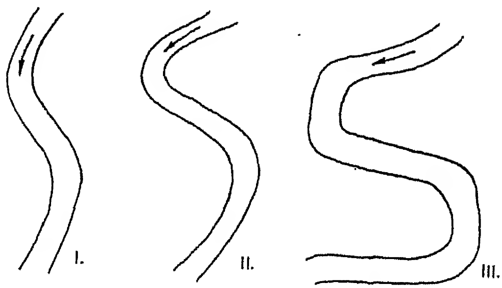

FIG. 110. Development of Meanders.

Mark Twain gives a good account of meanders and cut-offs in "The Mississippi Pilot."

After meanders have developed, a river may be rejuvenated and begin to cut down to a new base level. The meanders are then said to be incised, like those on the Wye where it

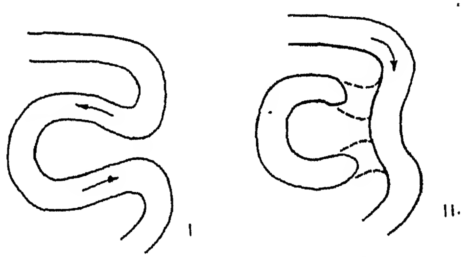

FIG. 111. Cut-off Meander and Ox-bow Lake.

cuts through the Carboniferous Limestone of the Forest of Dean. When an incised meander is cut off, it is left as a broad valley, often occupied by two little misfit streams, surrounding a meander core.

The maximum load that a river can carry depends on its energy, that is, on its volume and velocity. At any point where its velocity is checked it is liable to throw down some

of its burden as deposits of gravel, sand or mud. Thus at the foot of mountain slopes alluvial fans are formed, the stream constantly shifting its course as its bed gets choked with detritus. Lower down the valley there is deposition on the inner side of meanders, and in wandering across the plains a river may raise its channel, to the peril of the surrounding country in times of flood. This is the case with the rivers of Northern Italy and the Hoang Ho, "China's sorrow." On its banks and flood plain, the *lit majeur* of French writers, a river deposits sediment when in flood, and chiefly close to its channel, where the swollen current is checked, so that the flood plain tends to slope from the river to the valley sides. The natural banks or levees so formed are often heightened by artificial embankments.

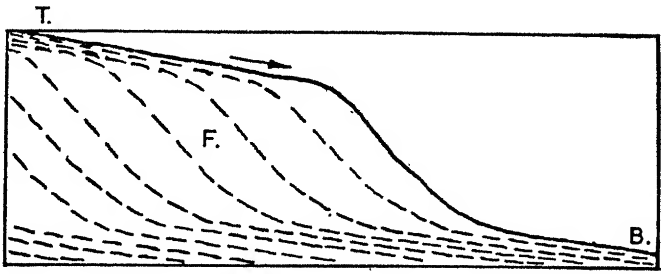

FIG. 112. Deltaic Deposits.
T—Topset beds. F—Foreset beds. B—Bottomset beds.

On reaching a lake the velocity falls almost to zero and all the debris is thrown down in a delta at the head of the lake or on the lake floor, a very clean river emerging at the lower end. Lake deltas are well seen in the English Lake District, and in Switzerland the town of Interlaken stands on the deltas of two streams that have separated the Lake of Brienz from the Lake of Thun.

In estuaries the salt water flocculates the mud and causes it to fall, in spite of a strong tidal scour, and the muddy nature of estuaries is well seen at Southend and Weston-super-Mare. In nearly tideless seas deltas are formed, that of the Nile, to which the name was first given, having the shape of the Greek letter Δ. The river splits into a number of dis-

tributaries, which may change their course with disastrous results; and deltaic deposits have a flat surface and a steep outer slope and often exhibit current-bedding. The greater part of river-borne silt and mud gets carried out to sea and distributed as marine clays over the continental shelf.

On the other hand, if either the velocity or the volume of a river is increased, senile impotence may give place to youthful activity, and deposition to renewed erosion. Such rejuvenation may be due to warping or uplift of the river basin; marine erosion, shortening its length and so increasing the gradient; capture of the waters of another stream; increased precipitation; melting of snowfields; or the reces-

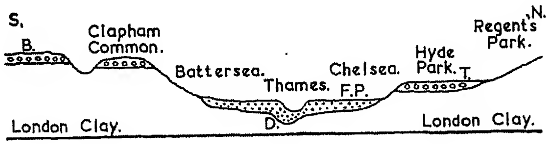

FIG. 113. Terraces of the Thames.
B—Boyn Hill Terrace. T—Taplow Terrace.
FP—Flood Plain. D—Deep Channel.

sion of a waterfall on the main stream past the end of a tributary. The result is that deposits of gravel, sand or mud are cut through and left as terraces on the flanks of the deepened valley, and meanders may be incised, like those of the Wye.

The Lower Thames and its tributaries show a good series of gravel terraces, periods of aggradation, in which gravel was deposited, having been terminated by uplift and renewed degradation. The Boyn Hill Terrace, about 100 feet above present river level, is represented by patches of gravel at Islington, Clapham Common, Croydon, Dartford Heath, Swanscombe and other places. The Taplow Terrace, with much brickearth overlying the gravel, lies some fifty feet lower and has suffered less denudation. It is seen at Acton, Hyde Park, the City, Mitcham and Crayford. The Flood Plain gravels border the river and are in places covered by Recent Alluvium. Borings show a deep channel cut during

a further uplift of too brief duration for the downcutting to work very far upstream.

The form of the cross section of a valley depends on the relative amounts of erosion that have been effected by the river in deepening its channel and by the subaerial agents in sloping the valley sides. The river by itself erodes a gorge or canyon, which is often a sign of a youthful river but which may persist in arid regions where subaerial erosion is slow,

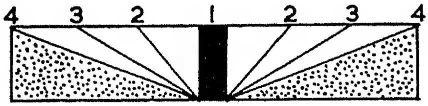

FIG. 114. Successive Cross Sections of a River Valley.

or in highly resistant rocks. The Niagara Gorge is only a few thousand years old, and the Grand Canyon of the Colorado, 200 miles long and from 3,000 to 5,000 feet deep, is cut through the Painted Desert of Arizona. Where rain erosion is active the narrow U-shaped gorge is widened out to a V of increasing width, which may be changed into a Y

FIG. 115. Cross Section of a Valley showing Asymmetry and Irregularity.

by rejuvenation and renewed downcutting. A meandering river also helps to widen its valley while aggrading its floor.

Resistant rocks may cause irregularities in cross section as well as in profile, like the scarp of the Inferior Oolite in some Cotteswold valleys. Strike valleys are often asymmetric, with dip-slope and escarpment facing each other.

A valley may remain narrow and gorge-like where it traverses resistant rocks, while it is broad and open in beds that are more easily eroded. The valleys of the Mole and the Medway have a more mature aspect on the Weald Clay and

the Gault than where they cut through the Chalk; and it is on the "softer" beds that the tributary valleys are formed.

The Weald gives good examples of the influence on river drainage of rocks offering different degrees of resistance to erosion. True, it is not a simple anticline, and the crest of the dome was planed off more than once; but nevertheless the principal rivers of the Weald flow down the dip slopes,

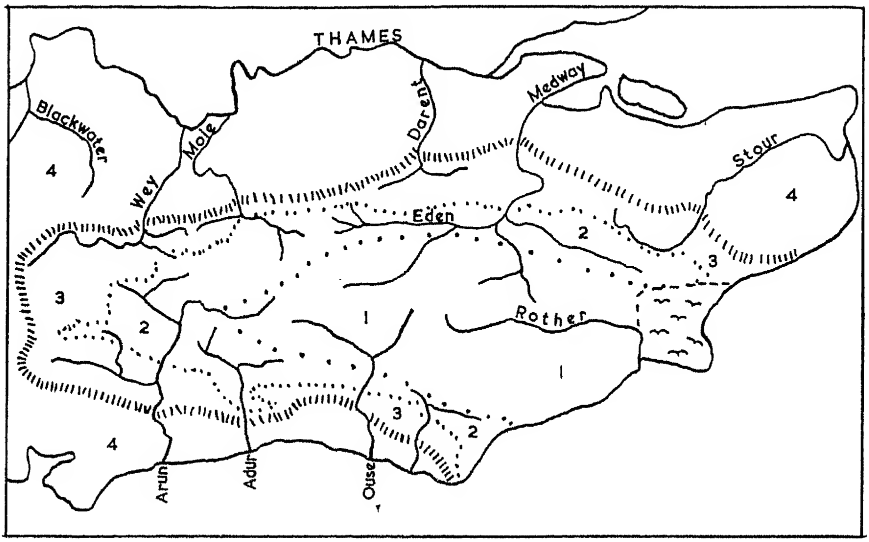

FIG. 116. Rivers of the Weald.

4. Chalk and Eocene. 2. Weald Clay.
3. Greensands and Gault. 1. Hastings Beds.

the Wey, Mole and Medway northward to the Thames, and the Arun, Adur and Sussex Ouse southward to the Channel. They are called consequent streams—flowing in consequence of the dip.

As the Weald Clay and the Gault were exposed, lateral valleys developed along their outcrops, cut by subsequent or strike streams. The Tillingbourne and the Pipp Brook, flowing west and east, are subsequent streams draining the Gault and Lower Greensand outcrops between the Wey and the Mole.

As the consequent rivers cut deeper the subsequent valleys were lowered too, and the escarpments of the Lower Greensand and the Chalk increased in height above the clay vales. Streams began to flow down from them in a contrary direction to the dip. Gibbs Brook, Kent Brook and the Shode, flowing southward into the Eden and the Medway, are examples of these obsequent streams, as they are called.

Consequent streams are not always transverse to the geological outcrops. The Thames, flowing eastward along the pitching axis of the London Basin, is just as much a consequent as the tributaries that join it from north and south.

Of two neighbouring consequent rivers, one may have the advantage over the other of greater volume, shorter course to the sea, or less obstruction from resistant rocks. It can therefore cut down more quickly than its neighbour, and its subsequent streams work back into the other's territory. Eventually a subsequent may capture the headwaters of the weaker river, which is then beheaded. The Western Wey formerly crossed the Chalk at Farnham and flowed down the Blackwater valley; but the Wey has beheaded the Blackwater. The Medway has the advantage of flowing into the sea instead of into the Thames, and it has worked westward, capturing the headwaters of the Darent. The dry valleys of beheaded streams often notch the escarpments as windgaps, like those above Merstham and Godstone.

River capture or piracy may be effected by consequent streams also. The Arun, favoured by a clear run to the sea and absence of Hastings Beds in its area, has pushed its watershed northward to the Lower Greensand escarpment at Leith Hill.

The Lower Severn has beheaded the Thames, which formerly flowed from Wales, and the Trent is another piratical river. In Yorkshire the eastward-flowing consequent rivers Wharfe, Nidd, Ure and Swale have been captured by the Yorkshire Ouse, itself a subsequent, on the soft Triassic sands, of the Humber, which has also captured the Trent.

It sometimes happens that a river behaves quite independently of the structure of the country. It may have been

flowing before folding began, and vigorous enough to maintain its course across new anticlinal ridges as they arose. Examples of such antecedent drainage are seen in the Columbia River cutting through the Cascade Range, and in some of the rivers of the Alps.

Or again the river may have started on a sloping surface of younger rocks lying unconformably on older ones. On cutting through the newer series the river reached the old rocks; but it was unable to alter its course to conform with their structure. This is called superimposed drainage, and it is well seen in the streams of Charnwood Forest, which started on Triassic Marls and now cut in an arbitrary man-

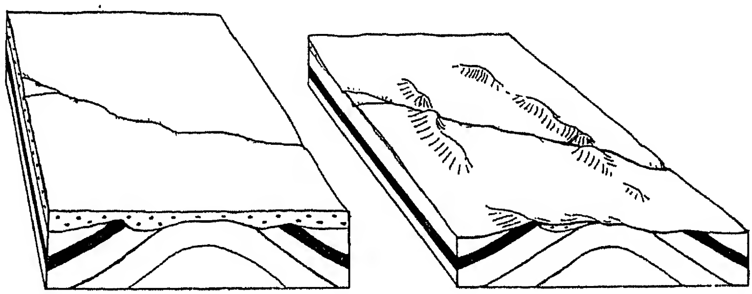

FIG. 117. Superimposed Drainage.

ner across ridges of hard Pre-Cambrian rocks, which were buried beneath the Trias. The Bristol Avon, too, probably started on the Trias and its course happened to lie above the ridge of Carboniferous Limestone that now forms Clifton Downs. Unable to shift, it cut a narrow gorge through the limestone, although there is a wide, open and more direct valley to the sea cut in the Trias. The Lake District is another example of superimposed drainage.

Rivers and the subaerial agents of erosion between them tend to reduce the land surface to one of very low relief, a peneplain. Between the great orogenic movements peneplanation probably reached an advanced stage, and we have to thank the Cainozoic crust movement for the highly diversified landscapes of the world to-day. Relics of old peneplains, deeply dissected and preserved in the concordant summit

levels of the mountains, are well seen in North Wales, the Lake District, and many other places.

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CHAPTER XVII

LAKES

MOST lakes are, like waterfalls, temporary phenomena in the development of a river, due to local irregularities in profile. But at least a dozen different modes of origin may be noted. Some lakes are due to crustal movements, warping or faulting. Glaciers are the cause of others, by excavating rock basins or by holding up water by a dam of glacial drift or the ice itself. In other cases the valley has been obstructed by landslips or by alluvial cones or deltas of side streams. The river alone is responsible for ox-bow lakes and lakes formed by jams of drifted timber. The sea has shut off some lakes by a spit of sand or shingle. In volcanic regions we have crater lakes and lakes held up by lava flows. There are depressions due to solution or weathering. And in the present century man has produced lakes on no small scale.

1. Warping of the crust has formed large depressions or geosynclines like those occupied by the Caspian Sea and the Great Lakes of North America. Warping of a river valley may cause lakes, such as Lake Geneva and those of the English Lake District. It has been suggested that the thick accumulation of ice in the Glacial Period depressed the central mountains, with a compensatory uprise of the peripheral region where the ice was thinner.

2. Faulting transverse to a valley may hold up water; and the irregular subsidence of the floor of a rift valley is responsible for the African lakes Nyassa and Tanganyika and for the Dead Sea.

3. Rock basins may be excavated by glaciers in relatively soft or shattered rocks when harder rocks crop out lower down the valley. At the foot of slopes, too, where the descent is checked, glacial erosion is increased for much the same reason that railway lines are worn away faster at curves than on the straight.

4. Moraine mounds often form a dam holding up the water of a lake, and the irregular surface of glacial drift is often dotted with lakelets or tarns. Such drift-dammed lakes are very common in Canada and the northern States, and in North Wales, the Lake District and Scotland.

5. The glacier itself, descending far below the snow line, may dam up the water in a side valley. Thus the little Mär-

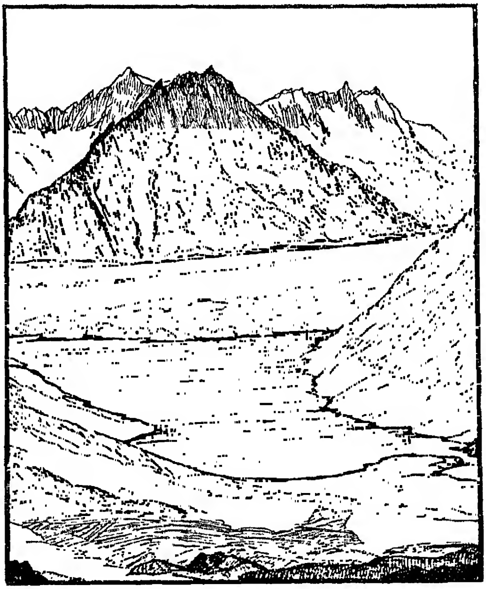

FIG. 118. The Märjelen See and Great Aletsch Glacier.

jelen See in the canton of Valais is held up by the Great Aletsch Glacier. The waning ice sheets produced many such lakes in this country. In Cumberland they have left overflow channels cut by the escaping torrents and lake deltas now high and dry. The Vale of Pickering was turned into a lake by the North Sea ice, and in Scotland the Parallel Roads of Glen Roy are successive shorelines formed by the lake held up by ice in the Great Glen.

6. Landslips often hold up lakes for a time. One lake so formed on the Upper Ganges in 1892 was five miles long and

700 feet deep. Two years later the dam broke and the impounded water rushed down the valley with disastrous results. Such dams and floods are of frequent occurrence in Northern India.

7. The delta of a tributary, or the alluvial cone below a rain gully, may also block a valley and form a lake above it.

8. A meandering river may show many examples of cut-off meanders, some of them still occupied by stagnant water. These are ox-bow lakes.

9. By undermining its banks a river often causes trees to topple into it. They are carried downstream and stranded in a shallow reach, where the branches entangle other drifting material and form a raft or jam which holds up the water and makes a lake. These are common occurrences in rivers like the Mississippi. The water generally cuts a new outlet for itself, and the reach in which the jam occurred is abandoned.

10. On the coast, waves and currents may drive a spit of sand or shingle right across a bay or the end of a valley. The Swan Pool, south of Falmouth, is a lake of this type. The Norfolk Broads occupy a silted estuary barred by the southward drift of sand along the coast.

11. Crater lakes, occupying the craters of extinct or dormant volcanoes, may be seen in the *maare* of the Eifel and in the little lake of Nemi, south of Rome. Crater Lake, Oregon, occupies a caldera and is five or six miles across and 2,000 feet deep.

12. A lava stream flowing into a valley may interfere with the natural drainage and form a lake.

13. Lake hollows may be formed by solution of limestone or other rocks, weathering, or the removal of material by the wind. Some of the meres of Cheshire are due to solution of salt beneath the surface.

Lakes have an equalising effect on temperature, and they also maintain a more uniform flow in rivers, preventing excessive flooding and drought. This is the function of many artificial lakes. A hydro-electric power plant on a river, for example, might be overwhelmed with flood water part of the year and left with a mere trickle at other times; but a suitably placed dam across the valley will impound a volume of

water sufficient to give a uniform flow all the year round. Other large reservoirs have been made for the water supply of cities, such as Lake Vyrnwy, which supplies Liverpool, and the many reservoirs in the valleys of the Thames and Lea. In arid climates man-made lakes supplying irrigation canals have enabled thousands of acres to produce crops that would otherwise have been useless desert.

Lacustrine deposits are of several different types. Coarse material brought down by a river is dumped as a delta at the head of a lake, and minor deltas may be seen forming wherever a streamlet enters a lake. These deltaic deposits, often current-bedded, push out over the finer detritus which covers most of the lake floor. Both sandy and muddy deposits may contain land and freshwater shells, insects, driftwood and other vegetable debris. Footprints of land animals may be preserved in the mud at the edge of a lake. The characteristic freshwater fossils include the univalve mollusca *Viviparus* (*Paludina*), *Limnæa* and *Planorbis,* the bivalves *Unio* and *Anodonta,* and the little bivalved crustacea known as ostracods, which are often very abundant. Shell marls form where mollusca are plentiful; and in some lakes diatomaceous earth occurs.

Chemical precipitates, too, occur among the deposits of salt lakes and soda lakes. If the evaporation from the surface of the lake balances the influx of river water, there can be no outflow, and the small amounts of soluble salts in the river water become concentrated in the lake and precipitated on its margin. The Great Salt Lake of Utah and the Dead Sea are examples of salt lakes. A dry climate, aiding evaporation, with rainfall on the hills supplying the rivers, are favourable factors; and the area of such lakes often varies with changes in evaporation and rainfall.

It should be noted that only the terminal lake in such a system of interior drainage becomes salt. The Sea of Galilee is a normal freshwater lake with none of the special features of the Dead Sea.

The Great Salt Lake, the shrunken remnant of a much larger body of water, still covers 2,000 square miles but is only about 15 feet deep. The chief salts in its waters are

sodium chloride (400 million tons) and sodium sulphate (30 million tons). Calcium carbonate is thrown down as oolitic granules near the shore.

Other lakes contain much sodium carbonate, and as desiccation proceeds this is precipitated as valuable soda deposits on the margin. Such are Lakes Natron and Magadi in East Africa. Borax is another product of certain lakes in Tibet and California.

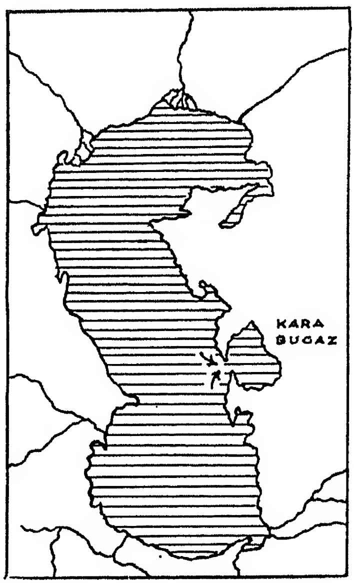

FIG. 119. The Caspian Sea.

Detached arms of the sea, in arid climates, may diminish in size and increase in salinity. Thus the head of the Gulf of California has been cut off by the delta of the Colorado River and now forms a nearly dry basin 300 feet below sea level, with a little salt water in the lowest part. The Caspian Sea, too, seems to have been cut off from the Arctic Ocean. It contains seals and other marine creatures. It is 3,200 feet deep and 85 feet below the Black Sea level, yet its waters are somewhat less saline than sea water. There is on the eastern side a bay, the Kara Bugaz, in which intense evaporation

maintains a constant inward current across the shallow bar, which prevents the denser highly saline water from flowing out. It is the Kara Bugaz, therefore, and not the Caspian, that shows the high salinity characteristic of interior drainage.

It is the destiny of most lakes to become silted up with deposits brought in by rivers, and organic material. Reeds and mosses contribute, forming bands of peat, or lignite in older examples. Swamp vegetation in the past has supplied our coal-seams. As most lakes are shallow the process does not take very long; but a few lakes are deep—Lake Baikal exceeds 4,700 feet in places—and they would be more persistent. Draining a lake by downcutting at the exit is generally a slow process, unless the barrier is ice or drift, since the river is handicapped by having left its tools on the bottom of the lake.

CHAPTER XVIII

THE SEA

THE destructive and much of the transporting work of the sea is due to waves, and waves are produced by wind. By friction the wind causes particles of water at and near the surface to move successively in circular orbits, and creates waves which increase in height as the wind continues to act on them. In the open ocean waves 30 feet high from trough to crest may be formed in a heavy sea, and with a wave-length of 200 to 600 feet from crest to crest. The greater the fetch, or distance from land to windward, the higher will be the waves produced by winds of the same velocity. Waves of

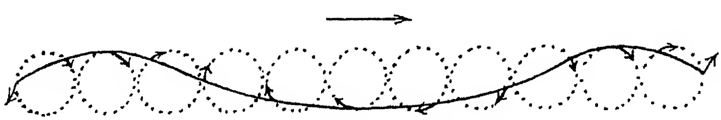

FIG. 120. Diagram to Illustrate Movement in Waves.

considerable size form on lakes, too; and reservoirs are often divided in order to limit the fetch, and with it the size of the waves.

In deep water it is only the form of the wave that advances, not the water itself, except that the surface layer may be driven forward by the wind and break as white caps. So also wave-forms may be seen crossing a wheatfield; yet the wheat remains where it was.

Beyond the area where they are acted on by the wind, waves travel onward with gradually decreasing height, forming a swell; and few unsheltered coasts are without waves, even on a windless day.

The size of the orbits described by the particles of water diminishes from the surface downward and becomes inappreciable at a depth equal to the wave-length.

When waves enter shallow water, where the depth is less than the wave-length, the bottom water is unable to move in circular orbits. The water moves to and fro in straight lines along the bottom and in elliptical orbits above it. Friction checks the velocity, and therefore the wave-length is reduced. The part of the wave nearest the shore is slowed down more than the part that is in deep water, and so the waves are refracted and tend to swing in nearly parallel to the shoreline. It follows that wave-energy is focused on promontories while bays receive less than the average amount.

In shallow water all the water under a crest is moving forward and all the water under a trough is moving backward,

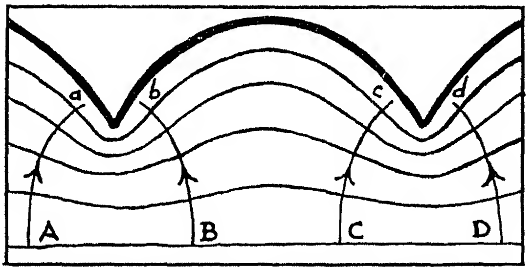

FIG. 121. Concentration of Waves on Promontories.

but with less velocity owing to the greater effect of friction. The water in a trough fails to move backward and upward sufficiently to build up the front of the next crest; the wave front grows steeper, and finally overhangs and breaks; the water runs up the beach as surf, carrying sand and shingle with it, and then runs back as undertow. The backwash may be concentrated into narrow swift streams running seaward called rip currents.

The waves seldom swing in exactly parallel to the shore, and so water, sand and shingle are thrown up the beach obliquely. But they run back down the steepest slope, at right angles to the shoreline, only to be caught up by the next breaker and again carried obliquely up the beach. Beach material is therefore carried in a series of zigzags along the shore, generally eastward on the south coast of England and

southward on the east coast. Groynes are sometimes erected to check this drift and retain the shingle.

The mere impact of a breaking wave is enough to move large blocks of stone if they are not securely fastened together. Air is compressed in joints and then sucked out as the wave falls back. Lighthouse doors are burst outward by waves owing to this suction effect. Compact rocks are therefore more resistant than jointed ones, and most igneous rocks than sedimentary ones.

But the waves do not work empty-handed. They use boulders, shingle and sand as their tools, hurling them repeatedly against the foot of the cliffs and cutting a notch there. The higher parts of the cliffs are attacked by the sub-aerial agents of erosion, aided by spray; joints are widened, and eventually a mass of rock falls, forming at first a protection but in the end yielding more tools for the onslaught of the waves.

Clay cliffs suffer rapid erosion, as at Sheppey. Wave action at the base is coupled with desiccation cracks that open at the surface in dry weather: subsequent rainfall enters these cracks and lubricates the clay below, and blocks of cliff slide bodily seaward.

Caves are formed by differential wave erosion along joints, faults or bedding-planes. Waves working along these lines of weakness from both sides of a promontory may erode a natural arch. Sometimes the inland end of a cave collapses and a funnel-shaped blowhole is formed from which a blast of spray issues as the waves break in the cave below.

Removal of the weak belt leaves the more resistant rocks isolated as stacks and rocky islets, such as occur off the coasts of Cornwall and Caithness. Cornwall also shows differential erosion in different kinds of rock, with coves and bays excavated in the slates and igneous rocks forming headlands.

As the sea advances, cutting back the cliffs, streams are rejuvenated by the shortening of their courses. Cliff waterfalls, gorges or chines are formed according to the relative rates of wave action and stream erosion.

At the foot of the cliffs a plain of marine erosion is cut. Such a plain, marking a Pliocene sea floor, is well seen at

a height of 400 feet round the Cornish coast, and it has also been traced in Wales. Farther off-shore a plain of marine deposition is formed.

The breaking wave throws large and small pebbles up the beach, but the backwash can only carry the smaller ones seaward. There is therefore a marked sorting and grading effect, and banks of shingle are deposited of about the limiting size that could be moved by the waves that formed them. There may be a storm beach of very large cobbles well above high-water mark, then coarse shingle, fine shingle and sand on the foreshore between tide marks. Fine shingle and sand infiltrate between the coarse pebbles, however. Some coasts may not yield the material for shingle, or even sand.

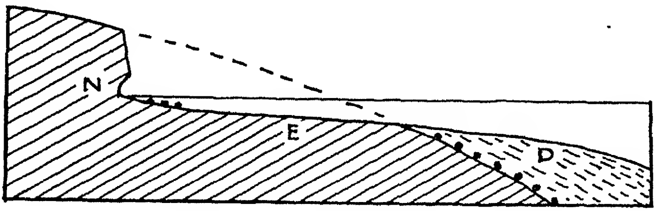

FIG. 122. Cliff Section.
N—Wave-cut notch. E—Erosion platform. D—Deposition.

In the sand grade, waves effect a sorting according to specific gravity, the denser grains being left near the head of the shore while the lighter ones are dragged down by the backwash. The Red River in Cornwall, flowing from the Redruth mining district, has carried much fluorspar and other lode material into St. Ives Bay, where the waves have formed a heavy-mineral concentrate near high-water mark which contains enough cassiterite to be worth working for tin. Black sands, rich in ilmenite or magnetite, are not uncommon; and the monazite sands of Ceylon and Travancore are similar wave-formed concentrates of ilmenite, zircon, monazite and other heavy minerals.

By continually being hurled up the beach and dragged back again, even hard stones like flint and quartzite become rounded to a degree that river transport can never achieve.

A blow struck by one flint pebble on another starts a cone of separation with its apex at the point of impact; and as the surface is worn down this cone is cut in ever-widening circles. These chatter-marks due to beach-hammering are seen alike on the flints of a modern beach and in ancient shingle deposits like the Blackheath Pebble Beds. There is little rounding of sand grains, however; their mass is too small and they are cushioned by a surface film of water.

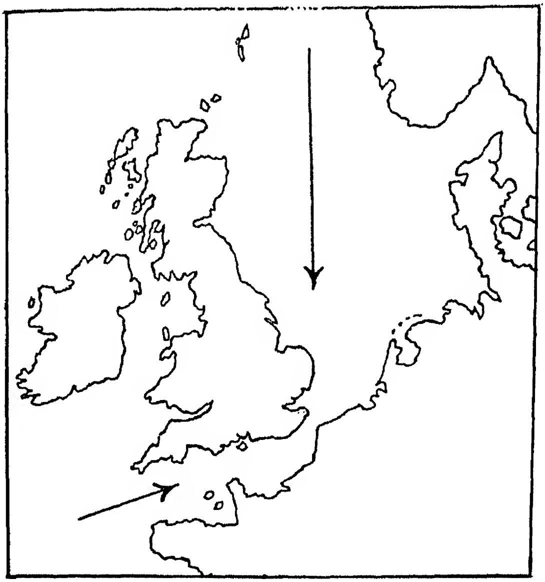

FIG. 123. Direction of Winds with the Greatest Fetch on the English Coasts.

Beach deposits differ from river gravels in their better rounding and sorting, and in the fact that the larger stones are in contact instead of being strung out in lines where the flood water dropped them.

The longshore drift of beach material has been attributed to currents, and especially to the flood tide which travels up the Channel and down the North Sea. This, however, has but little transporting power for sand, even where a strong

tidal race flows between an island and the mainland, though it does keep mud and silt in motion. The oblique incoming waves have far more effect. On the south coast the prevalent winds are from the south-west, and they have a greater fetch than winds from any other quarter and produce larger waves. So, except on sheltered shores, there is an easterly component in the breaking of most waves, and those the most effectual. Shingle and sand are carried eastward, as may be seen in the bars which force the Exe and the Axe to the eastern side of their valleys. At Bridport, however, the drift is in the other direction and fine shingle accumulates against the eastern groyne of the harbour entrance. Similarly on the east coast it is the northerly and north-easterly gales that have the greatest fetch and drive the beach material southward to form Spurn Head and the twelve-mile spit of shingle at Orford Ness.

Spits and bars due to longshore drift may grow out across the mouth of a bay, enclosing a lagoon that later becomes silted up. They may also tie an island to the mainland, as the Isle of Portland is tied by the Chesil Bank.

In many places the shoreline is receding through marine erosion, while at others it is advancing by accretion of shingle, etc., as at Dunge Ness. But similar changes may be due to fluctuations in the relative levels of land and sea. It is the fashion to refer to depression of the land or rise of sea-level as a positive movement, and to elevation of the land or fall of sea-level as a negative movement. These terms are badly overworked and convey little meaning; submergence and emergence are preferable, and they do not imply that it was the land that moved or the sea. Both types of movement have occurred in the Pleistocene and Holocene. The great ice-sheets of Europe and America abstracted water from the seas and returned it when they melted. This would give uniform or eustatic movements of emergence followed by submergence. But the weight of the ice-sheets caused an isostatic sinking of the area beneath them, with a corresponding uprise of the peripheral regions, giving a tilt; and the recovery after unloading of the depressed areas is still going on, for parts of Sweden are rising at the rate of

about two feet in a century while the extreme south of the country is sinking. Recent changes of level have resulted largely from a combination of these uniform eustatic and differential isostatic movements. Their effects are seen in several different ways.

Evidence for recent emergence (negative movement) is seen in the raised beaches that are common in northern regions, and which rise to 1,000 feet above sea-level on the

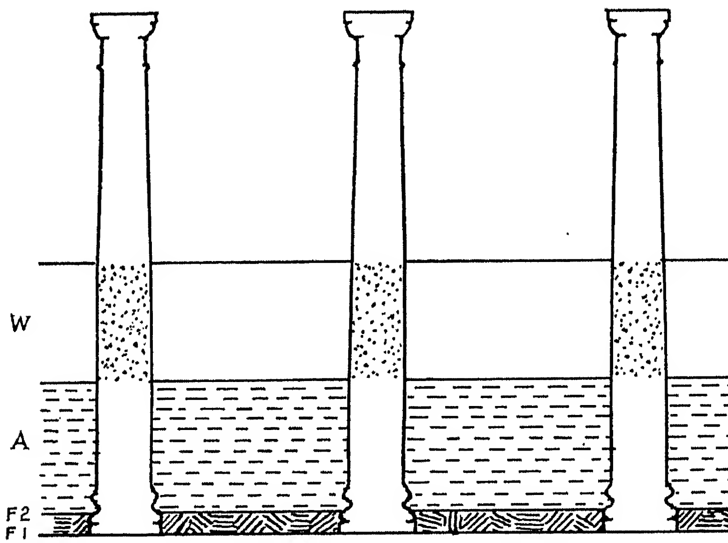

FIG. 124. The Serapis Columns at Pozzuoli at their Greatest Submergence.
F_1, F_2—Successive floors. A—Ash. W—Water.

west coast of South America. Rocks covered with barnacles occur well above high-water mark in earthquake regions. The raised beaches may be backed by old cliffs, fretted into caves, and with outlying stacks. An emergent coastline is a relatively straight one as a rule.

Submergence (positive movement) is indicated by the beds of peat in the Thames Alluvium, far below high-water mark, and by the submerged forests seen at many points round the

coast when the overlying sand has been swept away. They occur near Hastings, in Mounts Bay, and on the coast of Cheshire. Drowned valleys (rias) are seen in the estuaries of South Devon and Cornwall and of S.W. Ireland; and the marshes of Lewes and Amberley Wild Brooks in Sussex are due to the silting of wide submerged valleys.

A more spectacular instance is seen at Pozzuoli, near Naples, where the columns of a building known as the

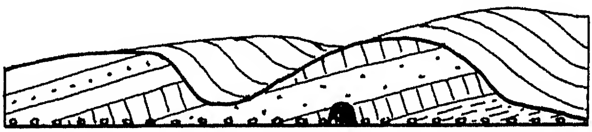

FIG. 125. Line of Raised Sea Cliffs, with caves and shingle.

temple of Serapis have been bored by marine molluscs to a height of about twenty feet above present sea-level, indicating a submergence of at least that amount followed by a partial recovery, for the floor is still 5 feet below sea-level. Other evidence suggests a post-Roman subsidence of 35 feet and a rise of 19 feet in this unstable volcanic region.

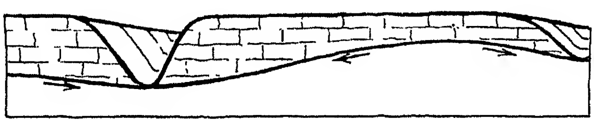

FIG. 126. Escarpment, with consequent and obsequent valleys.

The Chalk escarpments of the North and South Downs were at one time described as old sea cliffs cut during a marine transgression in the Weald. It is worth while to consider the differences between cliffs and escarpments.

(1) A line of old cliffs has a level base, often with raised beach material on it, and traces of old sea-caves may be visible. (2) The cliff top is irregular in height and often slopes up to higher ground beyond. (3) The cliffs often cut across the strike of the beds.

On the other hand, (1) the base of an escarpment is not level but commonly has a switch-back form and is occupied by the valleys of subsequent streams flowing in either direction toward the gaps cut by consequent rivers. (2) The top of the escarpment is remarkably level and marks the highest ground, being succeeded by a dip-slope. (3) The escarpment follows the strike of the beds.

The sea floors and their deposits may be divided into depth zones as follows :

——————— High-water mark
Littoral zone
——————— Low-water mark
Neritic zone
——————— 100-fathom line.
Pelagic zone

The deposits of the littoral zone are, as we have seen, shingle, sand and mud, all of them terrigenous deposits (*i.e.*, derived from the land). But organic deposits may occur in shell beaches and around coral islands, where terrigenous material is wanting.

The neritic zone includes the shallow-water areas of the continental shelves and epeiric or shelf seas such as the Baltic, Hudson's Bay and the Gulf of St. Lawrence, but not deep basins like the Mediterranean and Caribbean Seas. Waves and currents keep the water in motion to the bottom. Seasonal changes of temperature occur. Deposits formed in this zone are chiefly terrigenous, sands and muds; or where these are absent, organic. They are stratified and well sorted; may show current-bedding; may contain occasional land plants and animals as well as marine forms; and may include boulders and sand dropped by melting icebergs or entangled in the roots of drifting trees. The Grand Banks of Newfoundland are covered with ice-borne stones, and boulders of granite and other rocks occur in the Chalk. Some of the smaller stones may have been swallowed by fish or the extinct marine reptiles.

Life is abundant to the bottom of these shallow seas, as well as light and movement. Algæ support herbivorous molluscs and these feed carnivorous creatures. Diatoms swarm, and they are the staple diet of many kinds of fish. It

has been said that all flesh is grass and all fish diatom. The colder seas in particular are full of life, and here the great fisheries are found. Oxygen and other gases are more soluble in cold water, while in the warmer seas swarms of bacteria break up organic nitrates. But calcareous deposits are more frequent in warm seas.

The pelagic zone includes the intermediate slopes, from the continental shelf down to say 1,000 fathoms, and the ocean depths. The slopes are below the reach of waves and tides and are only affected by slow ocean currents, and the bottom is dark and cold, with no seasonal variation of tem perature; and in the absence of light there is no bottom vegetation. The deposits include the finest muds derived from the land, commonly blue-black in colour from the presence of finely divided ferrous sulphide in the form of pyrite or pyrrhotite. But in the Yellow Sea and off Brazil and Guiana the blue mud is replaced by red mud, from the enormous quantity of oxidised material brought down by the Hoang Ho and the Amazon. Green muds owe their colour to grains of glauconite, a hydrated silicate of aluminium, iron and potassium. There are also grey muds, of volcanic origin, and organic deposits.

The ocean depths, if taken as everything below the 1,000-fathom line, include parts of the Black Sea and the Mediterranean. The bottom is without light or movement, and the temperature is near the maximum density point of water, not far above freezing point. The organic remains come from creatures floating or swimming at the surface (plankton and nekton); but the cold water has so much CO_2 in solution that the thinner calcareous shells, and even siliceous remains, may be dissolved before they reach the bottom. The deposits show no terrigenous material but consist of fine oozes of organic, volcanic or cosmic origin. They are mixed deposits and are named after the dominant constituent. Thus we have the calcareous Globigerina and Pteropod oozes, the first characterised by abundant foraminifera and the second by thin-shelled floating molluscs, together with diatoms, clay, etc. The siliceous radiolarian and diatom oozes are dominated by these unicellular animals and plants.

But in areas where floating organisms are scarce, or more often where their tests have dissolved away, a red clay is found. This is essentially a residual deposit, practically free from lime, derived from the decomposition of pumice and other volcanic material. It is of extremely slow formation and generally yields the rarer products of the sea floor, such as the very solid and resistant earbones of whales and teeth of sharks, cosmic spherules, and minerals formed on the sea floor, such as phillipsite and manganese-iron nodules.

All these deposits may be tabulated as under.

MARINE DEPOSITS

Littoral Deposits, between H.W.M. and L.W.M., and Neritic Deposits, from L.W.M. to 100 fm.	Shingle Sand Mud Coral rock Nullipore sand, etc.	Terrigenous origin
Pelagic Deposits, beyond 100 fm.	Blue mud Red mud Green mud Volcanic mud Coral mud	
	Globigerina ooze Pteropod ooze Diatom ooze Radiolarian ooze Red clay	Pelagic origin

The average depth of the oceans is about 2,000 fathoms, or $2\frac{1}{2}$ miles, but in many places it is over five miles. The greatest depth known is 35,433 feet, or 6.7 miles, in the Swire Deep off the Philippine Islands.

The ocean floor was thought to be much flatter than the land surface, but recent echo-sounding surveys have shown that this is not the case. It is broken by volcanic cones, especially in the western Pacific, and by submerged mountain ridges, some of which emerge as chains of islands. There are plateau-like elevations, such as the Dolphin Ridge which stretches down the centre of the Atlantic. In some cases fault scarps occur, as in the Mediterranean, where a difference of 1,500 feet has been recorded between the bow

and stern of a ship. The continental shelves are cut by narrow canyon-like valleys running from the mouths of big rivers like the St. Lawrence and the Hudson to the edge of the shelf. The canyon of the Hudson River has walls 3,000 feet high, with a bottom 6,600 feet below sea-level. As no recent subsidence of this magnitude can be postulated, the cause of these canyons is a problem. Submarine currents, submarine springs, turbulence currents, earthquake waves and other agents have been suggested, but without carrying conviction.

The composition of sea water is remarkably uniform. It yields on evaporation about 3.44 *per cent.* of mineral matter with the following composition :

$NaCl$	77.76 *per cent.*
$MgCl_2$	10.88
$MgSO_4$	4.74
$CaSO_4$	3.60
K_2SO_4	2.46
$CaCO_3$	0.34

This is very different from river water (see p. 183) in which $CaCO_3$ is most important while $NaCl$ is much less abundant. Both $CaCO_3$ and SiO_2 are continually being abstracted from solution by animals and plants to form their shells, bones, and so on, while there is no such withdrawal of salt.

There are also gases in solution, especially N, O and CO_2, and more in cold waters than in warm. CO_2 is produced by organisms and volcanic vents, as well as being taken from the atmosphere. Oxygen is constantly being withdrawn by animals and does not have a chance of diffusing downward very far.

Such variations in salinity as do occur are due to variations in evaporation and in the supply of fresh water from rainfall, rivers and melting ice. The surface water of the sea has a density between 1.024 and 1.03 at 60° F.; while at a depth of five miles the density is 1.06.

The surface temperature of the ocean varies between 80° F. in the tropics and 28° F. in polar regions, at which point freezing begins. But the isotherms do not follow the lines of latitude very closely, owing to warm and cold currents.

Shallow enclosed seas in low latitudes are very warm, the Red Sea having temperatures of 90° and even 100° F.

The temperature of the water below the surface falls off, abruptly where cold polar currents occur. But in enclosed seas the fall in temperature is not continuous. Thus in the Red Sea it drops from 90° F. at the surface to 70° at 1,200 feet, and then remains nearly constant to the bottom at a depth of 3,600 feet. In the Mediterranean the drop is from 75° at the surface to 55° at 750 feet, while the bottom at 13,000 feet has about the same temperature, although at that depth in the open ocean it would be 37°. This is due to the barriers at the entrance to these seas which keep out the cold bottom water of the ocean; and so the temperature remains about that of the open sea at the level of the barrier.

It is the polar ice-caps that by their melting cool the seas and powerfully affect the climate. Ocean currents are produced partly by differences in density due to temperature and salinity, but more by the drag of constant winds like the trades and anti-trades. Currents, too, have great influence on the temperature and humidity of adjacent lands—compare Ireland with Newfoundland, which lies farther from the pole.

There remains one problem to be considered, that of coral formations. The coral polyp (it is not an insect) resembles a sea-anemone in having a simple body cavity, mouth and tentacles; but it secretes a calcareous cup divided by septa running toward the centre. In the red coral there is only a rod-like base supporting the polyps. By budding the coral polyps form colonies which may be branching and tree-like, or hemispherical masses up to fifteen feet across.

The reef-building corals are rather particular as to the conditions in which they will grow. The water must have a mean temperature not lower than 68° F. and be clear and salt. It must also be shallow, preferably under 25 fathoms and certainly not more than 50 fathoms. Light is needed by the algæ living symbiotically with the corals. Abundant food supply is also necessary, such as is brought by the westward currents of tropical oceans.

Coral deposits consist of dead coral colonies, broken fragments, the remains of fish that swam among the corals,

molluscs, foraminifera, calcareous algæ such as nullipores, and other organisms. They are cemented into a compact mass by the solution and recrystallisation of calcite, and there is slight dolomitisation, some of the calcium being replaced by magnesium from the sea water.

This solid mass, with corals living on its upper and outer parts, rises to about low-water mark, for corals cannot be exposed to air for long. It is then the outer corals that thrive best, since there is more food among the breaking waves. But waves may pile up broken coral above tide marks, with coral and nullipore sand, and so build small low islands.

There are three types of coral structures, fringing reefs, barrier reefs and atolls. Fringing reefs extend outward from

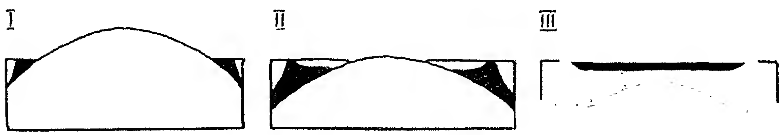

FIG. 127. Coral Reefs : Subsidence Theory.

the shore, forming a narrow fringe on steep coasts and a wider one where the slope is less. The corals grow chiefly on the outer edge, on a talus of coral debris. There are gaps opposite streams, for fresh and muddy water kills the corals.

Barrier reefs have a channel between them and the coast. The Great Barrier Reef extends for 1,200 miles along the east coast of Australia, 20 to 30 miles from the land, with 15 to 50 fathoms of water in the channel. Many volcanic islands in the Pacific have barrier reefs also.

Atolls resemble barrier reefs except that there is no island in the centre. They are ring-shaped, from 2 to 50 miles in diameter, with a central lagoon averaging 30 fathoms in depth. The outer edge slopes steeply down to very great depths. Many atolls support well wooded and inhabited islands.

The formation of fringing reefs presents no difficulty, but barrier reefs and atolls seem to rise from ocean floors at

depths far greater than corals can tolerate, and the problem is to account for their early stages.

The obvious suggestion is that the sea floor was formerly within the limits of coral growth and has sunk, the corals keeping pace with the sinking. This theory was propounded by Darwin and amplified by Dana. An island, possibly of volcanic origin, acquired first a fringing reef: as this sank the corals on the outside grew upward but those inside were starved, and a barrier reef was formed; and further sinking submerged the original island, giving an atoll. This idea is supported by a boring put down at the atoll of Funafuti, which penetrated 1,100 feet of coral rock before the boring tool broke; and at Maratoea a bore penetrated 1,500 feet of

FIG. 128. Coral Reefs: Accumulation Theory.

calcareous material—reef and lagoon deposits. Darwin cited the foundations of stone houses now below sea-level as evidence of subsidence; and the coast lines of volcanic islands with barrier reefs show no cliffs but drowned valleys and irregular shorelines. On the other hand, it is hard to account for the necessary subsidence of thousands of feet over some 20,000,000 square miles in the Pacific alone; Darwin's houses were really pens for storing coconuts in sea water; and the Pelew Islands show raised coral reefs up to 400 or 500 feet, with atolls only sixty miles away.

Murray tried to get over the subsidence difficulty by postulating some platform raised to within the limits of coral growth. It might be a volcanic island cut down by the waves, or a volcano that never reached the surface. Or it might be a low ridge on which foraminifera and other organisms accumulated till the requisite height was reached. On such a platform corals grew upward, moving outward on a talus of fragments. Again the outer corals throve, and the central

mass of dead corals was bored by molluscs, crumbled, and dissolved, forming a lagoon. But a lagoon 40 miles wide and 200 feet deep could scarcely be formed in this way, and indeed the lagoons are silting up with calcareous deposits and not getting deeper.

Daly's glacial control theory is based on changes in sea-level, not the ocean floor. The great ice-caps of the Pleistocene covered millions of square miles with ice several thousand feet thick. This lowered the general level of the sea, and the gravitational attraction withdrew more water from the tropics. The total effect has been estimated to be 200 to 250 feet. Owing to the cold, corals were confined to a narrow tropical belt. Islands of dead coral were cut down to sea-level or terraced; and when the ice melted and the water

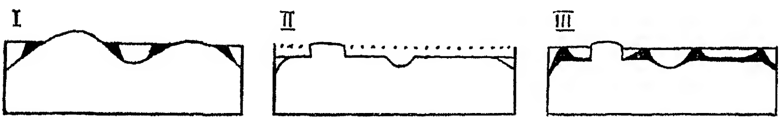

FIG. 129. Coral Reefs: Glacial Control Theory.

returned the corals spread in the warmer water and built atolls on the platforms and barrier reefs around the terraced islands. It may be that all three theories are true in part, and other factors too may have operated, such as warping of the ocean floor.

Coraliferous limestones are common in England, as in the Devonian of Torquay, the Carboniferous Limestone, and the Coral Rag of the Upper Jurassic. But the corals are mixed with crinoids, molluscs and other organisms and rarely form coral reefs.

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CHAPTER XIX

ICE

LEAVING frost action to a later chapter, we deal here with ice on lakes, rivers and seas and the greater masses that form glaciers and ice-sheets.

While water is exceptional in expanding at the moment of crystallising or freezing, ice, like most solids, contracts as its temperature falls. The first-formed ice on a lake, therefore, is put in a state of tension as the winter advances and the temperature falls far below freezing point, and it may either pull away from the shore or crack, with loud reports. Fresh ice forms in the cracks. When the temperature begins to rise again the ice expands. It is then too big for the lake and exerts a thrust on the shores, throwing alluvial ground into ridges or building stone walls of beach material. Such walled lakes are common in Canada and the northern States. Marshy soils contract in the same way, forming ice wedges.

In rivers, while the upper water is still flowing, ground ice may form around stones on the bottom and float them up; and these, as well as stones frozen into the surface ice, are carried downstream when the thaw comes. Ice jams may form, endangering bridges, and causing floods and increased erosion when they break.

On the sea the temperature must fall below 28° F. before freezing occurs, owing to the salinity. The ice formed consists of crystals of pure ice, but there may be inclusions of brine or salt crystals.

In polar regions the sea water freezes along the shore, and snow accumulates on it. This sea ice breaks up into floes which form the ice-pack and may freeze together again. The ice foot rises well above sea-level and is formed of the first sea ice, snow, spray, and debris from the cliffs above.

Snow-fields, in which the snow does not all melt in the summer, are formed at heights of 15,000 to 18,000 feet near the equator and at sea-level in polar regions. Small snow-fields occur on most mountain chains; but all these together would not equal the snow- and ice-cap of Greenland, and the Antarctic ice-sheet is many times larger. If all the snow and ice now on the land were melted it would raise the ocean level some 30 feet.

The height of the snow-line, above which snow remains throughout the year, depends on several factors. Temperature is obviously one of them, driving the snow-line high in low latitudes and dropping it to sea-level near the poles. But the amount of snowfall is also important, since a little snow is soon melted. Moisture-laden winds from the S.W. carry much snow to the southern slopes of the Himalayas and bring the snow-line there lower than on the northern side, although they are nearer the equator and face the sun. In the Andes the moist Amazon basin, almost like an inland sea, lowers the snow-line on the east of the chain. Other factors are aridity of the air, which hastens evaporation of snow, and topographic relations, which may favour accumulation and check melting, or *vice versa*. Some examples of the height of the snow-line in different regions are listed below.

HEIGHT OF SNOW-LINE ABOVE SEA-LEVEL

Andes, West side, near Equator,		about	18,500	feet.
,, East ,, ,, ,,		,,	16,000	,,
Himalayas, North side,	lat. 38° N.	,,	16,700	,,
,, South ,,	,, 28° N.	,,	13,000	,,
Alps,	,, 46° N.	,,	9,000	,,
Lapland,	,, 70° N.	,,	3,000	,,
Scotland, just above the top of Ben Nevis, where snow sometimes remains through the summer.				

Alternate melting and freezing (regelation) and the pressure of overlying snow gradually convert snow-fields into ice-fields. A coarsely granular ice is first formed, known as *névé* or *firn,* and then compact ice.

From the snow-fields tongues of ice creep down the valleys as glaciers. The upper part of a glacier is snow-covered, but, except in winter, the lower part has a very dirty appear-

ance, owing to the rock-debris in the ice, which is concentrated at the surface as melting proceeds. The ice may be quite concealed by such debris.

A large stone, having a low conductivity for heat, protects the ice below it from the sun. It is left on a pinnacle of ice as the surrounding ice melts, and forms a glacier-table. Accumulations of debris are left on ridges of ice in the same way. But a thin flake of dark shale is quickly heated through by the sun's rays and melts a little pit in the ice beneath it. So, too, thin patches of dust are let down into dust wells.

The sides of a glacier are littered with frost-shattered debris from the valley sides, forming lateral moraines. Below the confluence of two glaciers two lateral moraines unite, and a large glacier may be streaked by several of these median moraines, as they are called. There is also much material

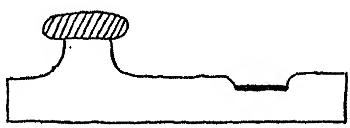

FIG. 130. Stones on Ice.

carried unseen within the ice, the englacial moraine. At the melting end of the glacier all this transported load, except such as can be carried away by the melt-water, is thrown down in a terminal moraine.

The cross section of a glacier is convex, higher at the centre than at the sides. The profile roughly follows that of the containing valley, but it may terminate in a steep slope.

A large glacier may descend far below the snow-line before melting, 5,000 feet in the Alps. In southern Alaska glaciers come down to sea-level in the latitude of Carlisle, 55° N.; and in the South Island of New Zealand, lat. 45° S., they descend into sub-tropical forests with tree-ferns. These are not mere geographical facts: they have a bearing on some contradictory climatic evidence associated with past glaciations.

An increase in the gradient of the valley floor accelerates

the glacier, and crevasses open transverse to its course. Below the steep place they tend to close up again; but melting has widened them too much for them to heal completely. Streams of melt-water cut up the ice and fall down crevasses to join the subglacial stream. Seracs and ice-pinnacles stand up between widened crevasses, and the ice surface is by no means a skating rink.

The movement of glaciers, as of rivers, is retarded by friction with the bottom and sides, and is greatest in the centre

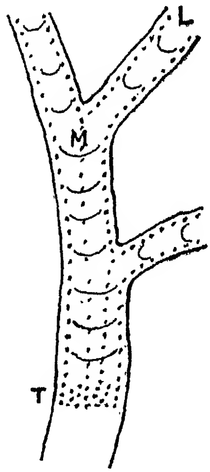

FIG. 131. Moraines.
L—Lateral. M—Median.
T—Terminal.

of the top surface. A row of stakes driven in a straight line across a glacier assumes an arcuate form after a few years. The drag of the bottom and sides also causes crevasses and thrust planes in the ice. The movement is very slow, usually less than a foot or two a day, but one very large glacier in North Greenland is said to move 100 feet a day. Conditions favouring more rapid movement include great thickness of ice, a steep gradient, a smooth bed, high temperature (for ice), and much water in the ice. It follows that the velocity is greater in summer than in winter.

Since ice can be moulded to any form, given sufficient pressure and time, and glaciers become narrower or broader to fit their beds, it was thought that ice moved like a highly viscous liquid, such as pitch. But no liquid would crack open in passing irregularities in its bed, or form vertical-sided flows with longitudinal crevasses like many glaciers in high latitudes. Ice is crystalline, not amorphous. It melts abnormally, with decrease in volume, and so pressure lowers the melting point. There is therefore melting in regions of high pressure and the water migrates to points of lower pressure and freezes there. Surface water, too, melted by

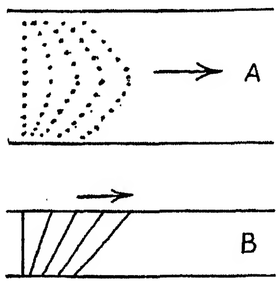

FIG. 132. Rate of Glacier Movement, in plan and section.

the sun, descends and freezes, its expansion helping to move the ice downward. The ice crystals have the power of yielding to strain by gliding along the basal plane, just as calcite has gliding planes parallel to the faces of a rhombohedron. All these help the ice to flow, and there is also shearing in the mass of the ice, the upper part sliding over the lower and projections in the bed causing thrust planes by which the lower ice may override the upper.

Valley glaciers are sometimes called Alpine glaciers, since they were first studied in the Alps. Sometimes the ice falls over a precipice and joins up again in the valley below as a reconstructed glacier. Piedmont glaciers are wide spreads of stagnant ice where valley glaciers descend to the plains before melting. The Malaspina Glacier in Alaska is an

example: it is 1,500 square miles in extent and is in places covered with earth and stones supporting dense forests, though there is 1,000 feet of ice below.

Ice-caps of very great extent occur in Greenland and the Antarctic continent. The whole of Greenland is covered with snow and ice except for the margin and a few mountain peaks that rise above the ice-sheet as nunataks. The ice forms a gently sloping dome 10,000 feet high and creeps slowly outward; it is smooth inland, but much crevassed near the coast; and it escapes through many large valley glaciers which descend to sea-level and there break up to form icebergs.

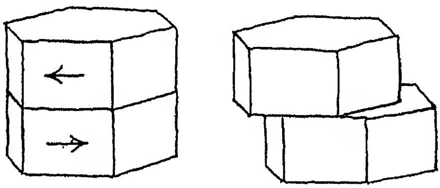

FIG. 133. Basal Gliding Plane in Ice Crystal.

The Antarctic ice-cap reaches 9,000 feet above sea-level and, descending through valley glaciers, pushes out over the sea as the Great Ice Barrier.

In places on the surface of the floating ice-sheets of the Antarctic, and stranded on the coast where they have receded, are patches of marine mud with organisms undisturbed, and also of crystalline mirabilite ($Na_2SO_4.10H_2O$). The ice here has a very slow movement and is rapidly wasting at the surface, from summer thaw and evaporation. It is inferred that fresh ice forms from the sea water below. During a cycle of cold years accession of ice to the base may exceed the loss at the surface; the thickness then increases, and the ice grounds at some points, where the sea floor becomes frozen into the sheet. Enclosed bodies of sea water are concentrated by freezing till mirabilite crystallises out. A warmer spell will diminish the thickness of the ice, which floats again; more ice forms below the patches of mud and

mirabilite; ice above them melts, and so they rise gradually to the top of the floating ice-sheet. This may be one factor in the formation of the high-level shelly drifts found on both sides of the Irish Sea, up to 1,400 feet above sea-level at Moel Tryfaen, near Nantlle. Overthrusts in the ice as it came ashore may have helped in elevating these marine sands, which do not prove a submergence of 1,400 feet as was formerly claimed. Many supposed raised beaches may have a similar origin.

As in the case of rivers, the work of glaciers and ice-sheets includes erosion, transport and deposition; but opinions differ as to the efficacy of glacial erosion as compared with

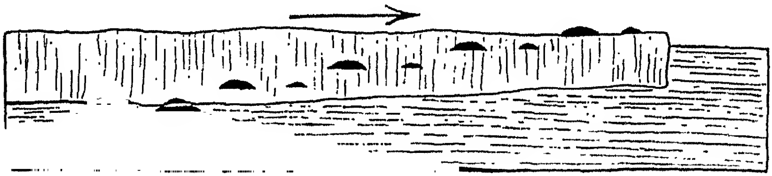

FIG. 134. Diagram showing how Patches of the Sea Floor may rise intact to the surface of a floating ice-sheet.

river erosion. On the one hand some writers attribute the whole excavation of a glaciated valley to ice action; on the other, ice is regarded as a cover protecting the underlying rocks from erosion. Both these extreme views are wrong. A thin sheet of ice has certainly a protective function, and glacial erosion increases with the thickness of a glacier or ice-sheet; but most glaciers have occupied valleys already cut by rivers in pre-glacial or interglacial times; and the subglacial stream of melt-water also plays its part in deepening the valley.

Any soil and loose rocks are readily frozen into the ice and carried along with it, and so the ground over which an ice-sheet has passed may show large areas of bare rock, as in parts of Ontario. Solid rock is more difficult to move, but upstanding masses show steep crags on the lee side, where

blocks have been plucked away by the ice, while the up-stream slope is worn smooth, although ice is much softer than most rocks. These characteristically shaped rocks are known as *roches moutonnées,* because they look rather like sheep lying down. The rock surface may be scratched and grooved by stones and boulders frozen into the bottom ice, sometimes showing fine striæ, sometimes grooves a foot or more across.

On the other hand, a very resistant rock such as a volcanic neck may protect softer beds behind it from erosion, forming a crag and tail. The Castle Rock at Edinburgh is a basaltic plug forming such a crag, while the High Street

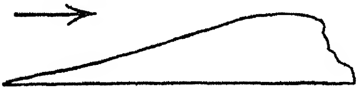

FIG. 135. Roche Moutonnée.

FIG. 136. Crag and Tail.

runs eastward down the tail on sedimentary rocks that were sheltered from the ice that cut a deep valley on either side.

A glacier does not readily adapt itself to the winding course of a river valley. It grinds against the projecting spurs and cuts them back to precipitous slopes; and in time the whole valley may be broadened, straightened and side-steepened, and the winding V-shaped river valley converted into a straight U-shaped glacial trough. This is very much broader than the narrow U-shaped gorge of juvenile river erosion.

Above the glacier trough the valley may show shoulders, relics of an old river valley; sometimes several shoulders one above another. In Switzerland these shoulders support the mountain pastures or alps that have given their name to the mountains themselves. The higher peaks are sharpened by frost action.

The deepening of the valley is due partly to the sub-glacial stream, which is rapid and armed with material of all grades from mud to boulders. Both deepening and

widening are greater in a main valley, occupied by a large glacier, than in side valleys. These, therefore, cannot keep pace with the main valley and are left as hanging valleys when the ice has gone, their streams joining the main valley by waterfalls or gorges. The example of the Aare valley and the Reichenbach Fall has already been mentioned.

Excavation by the glaciers themselves, forming rock basins, may take place in such rocks as limestones, which are relatively soft and soluble, or at the foot of slopes, or where a broad shallow glacier is narrowed and deepened by a constriction in the valley. It might be inferred that when a basin has been excavated well below the level of the sill or threshold, the bottom ice will remain stagnant and ineffectual while the ice above slides over it. But in fact we find

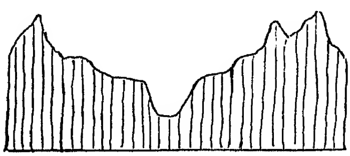

FIG. 137. Glaciated Valley, with Shoulders.

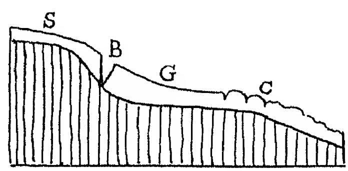

FIG. 138. Junction of Snowfield with Glacier.
S—Snowfield. B—Bergschrund. C—Crevasses.

that glacial lakes with rock bars have a depth of hundreds of feet, and so do the fjords of Norway, which have shallow sills. In East Anglia valleys 300 or 400 feet deep have been excavated and filled with glacial drift. No satisfactory explanation of these deep excavations has yet been given.

The profile of a glaciated valley is more irregular than that of a river valley. Besides lakes and rapids, steps in the floor are frequent. On the protectionist theory they mark halting places in the retreat of the ice, the glacier protecting the floor above the step while the valley below was excavated by the river issuing from the ice. River rejuvenation fol-

lowed by glaciation has also been suggested. Overdeepening below the confluence of two glaciers may account for some steps. Any increase in gradient may cause crevasses, down which surface water falls and saps the rock by frost action and plucking. Steps so formed will work back toward the head of the valley. One important step is the trough-end, the steep, semicircular end of the valley, formed where wide snow-fields converge to form a narrow glacier and the increase in thickness and velocity speeds up erosion.

Another feature of glaciated regions is the cirque, cwm or corrie. This is a semicircular hollow with precipitous back and sides, a flat or concave floor which may be occupied by a lake, and a step between the floor and the main valley. It has been likened to an armchair. Cwm Idwal in Caernarvonshire is a good example. Like the trough-end, which it resembles, the cirque may owe its origin to the bergschrund or highest crevasse, which separates the snow-field from the glacier proper. Water falling into the bergschrund by day is said to freeze nightly, splitting the rock below and dragging it away. But many cirques have little gathering ground for any snow-field above them. Nivation, or the daily alternation of frost and thaw on the edge of a waning snow-field, may have initiated the hollows.

Two adjacent cirques eat into the intervening ridge and reduce it to a narrow edge or *arête,* like Striding Edge and Swirrel Edge on Helvelyn. Three or more cirques may by erosion produce a pyramidal peak like the Matterhorn.

An ice-sheet reduces the relief of the country it passes over, smoothing out the hills. It polishes and striates the rocks, the grooves and striæ showing the direction in which the ice moved. This is also shown by the *roches moutonnées* and the crag and tail features. Transported blocks often indicate the direction of movement, as in the train of blocks of Silurian greywacke at Norber in the West Riding, or the granite boulders which were carried from Shap through the Stainmore gap and strewn along the Yorkshire coast.

Stones in the ice are rubbed smooth and striated like the rock floor. The final product is a sort of rock flour, and all grades from this to huge boulders are carried on the ice and

in it. Some of the debris comes from the valley sides, loosened by frost or brought down in avalanches. Some falls down crevasses and joins the material plucked from the bottom of the valley to form a bottom or englacial moraine which may greatly exceed the moraines visible at the surface. In ice-sheets surface moraine is limited to the neighbourhood of nunataks, mountain summits that project through the ice, and the lower parts where much melting has taken place.

This transported material is dropped at various points. Some is deposited in the bed of the subglacial stream, and some is stranded on the valley side as the ice begins to shrink. Great blocks left, often in delicate balance, where neither water nor gravity could have brought them, are known as perched blocks. If the end of a glacier remains stationary for some time, a thick terminal moraine is formed; but if snowfall increases or melting diminishes the glacier will advance and sweep it away. It is therefore the moraines formed during the latest retreat of the ice that are the most conspicuous.

When an ice-sheet melts, glacial drift is spread over all the area it occupied, except for occasional bare patches where the ice was free from debris. This drift or boulder clay, which covers large parts of our Midland and Northern counties, is thickest in the valleys, and so tends to diminish relief; but its surface may be hummocky, with depressions containing ponds and marshes. The last isolated blocks of ice, as they melt, shed much of their debris on their flanks, and when they have finally disappeared their sites are occupied by hollows or kettle-holes in the moraine.

Terminal moraines often pond back the water coming down the valley and form lakes, and lateral moraines sometimes hold up lakes too. Temporary lakes are formed by the ice itself, like the Märjelen See (p. 135). Ice occupying the Great Glen of Scotland held up lakes in the side valleys, and successive shore-lines of these lakes are seen in the Parallel Roads of Glen Roy. Other ice-dammed lakes in Cumberland and elsewhere are indicated by beaches and deltas, and by the channels cut by their overflow torrents. The

Yorkshire Derwent in pre-glacial times flowed eastward into the sea near Scarborough; but its waters were ponded back by ice in the North Sea and cut a narrow gorge south-westward into the Vale of York. When the ice retreated a drift dam obstructed the old exit, and the river now flows westward, with reversed drainage. The Upper Severn formerly flowed into the Dee; but glacial diversion led it to cut the gorge at Iron Bridge and flow southward instead of north.

Vigorous streams issue from the end of a glacier or edge of an ice-sheet. They spread out the glacial debris in what are called fluvio-glacial deposits, grading the material and

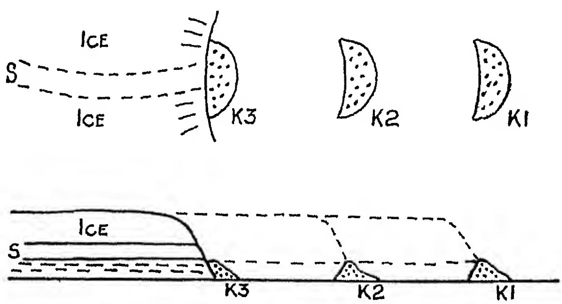

FIG. 139. Esker and Kames, in plan and section. S—Stream. K_1, K_2, K_3—Kames.

dropping the stones first and then sand and mud. Streams from an ice-sheet may not find a valley; each stream forms its own outwash fan, and these coalesce to form an outwash plain. The sheets of gravel spread over the lower slopes of the Chiltern Hills exemplify this.

Streams under or in the ice build deposits of gravel and sand. These are contained between walls of ice, and when the ice melts they are left as embankments which are called eskers. Some eskers however may have been formed by successive mounds of debris dropped at the mouth of a subglacial stream. These mounds are large where the ice-front

has halted for some time, smaller during periods of retreat to the next stand-still place; and the result is a beaded esker.

Normally the subglacial stream, losing velocity on emerging from the ice, throws down a mound of ill-stratified material roughly transverse to the ice movement. This is a kame, and many terminal moraines show a succession of kames. Drumlins are short ridges in the direction of movement, of uncertain origin.

Icebergs are formed where glaciers or ice-sheets enter the sea, and they, too, carry debris frozen in the ice, dropping it as they melt. In this way stones and boulders are incorporated with marine deposits of finer grade. Quantities of boulders are dropped by icebergs on the Grand Banks of Newfoundland; but the supply is not sufficient to have built up the Banks themselves, as has been suggested.

During much of the Pleistocene, or last glacial period, the Alpine glaciers spread into the plains of North Italy as well as northward. Northern Europe was covered by an ice-sheet that radiated chiefly from Scandinavia and covered Britain north of the Thames, all northern Germany and much of Russia. Another great ice-cap covered Canada and the northern States. There is evidence of other glacial periods in the Pre-Cambrian and the Permian.

To sum up, we may collect the chief characteristics of a region that has been glaciated. There are first the wide U-shaped valleys, with truncated spurs, steps in the floor, and hanging valleys on the flanks. The higher ridges are sharpened by frost. The rocks are smoothed and striated. Rock basins are excavated and occupied by lakes, and there is evidence of the ponding back of water and its escape through overflow channels.

Perched blocks, and those brought from a distance, are good evidence for transport by ice, and so is the striation of stones in the deposits, which are unsorted and unstratified. The deposits may take the form of regular embankments (eskers) or smaller mounds (kames and drumlins). And the surface of the deposits may show kettle-holes and other depressions, sometimes occupied by lakes.

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CHAPTER XX

WIND

HAVING considered the solid earth, or lithosphere, and its liquid cover, the hydrosphere, we now come to the earth's outermost envelope or atmosphere. The principal agents of atmospheric or subaerial erosion are wind, heat and cold, frost and rain.

Let us first consider the composition of the atmosphere. Dry air is composed of

Nitrogen	about	78 *per cent.* by volume.	Carbon dioxide	0.03 *per cent.*
Oxygen	,,	21	Hydrogen	0.01
Argon	,,	1		

The amount of water vapour in the atmosphere is variable, and so is the amount of dust.

Oxygen is absorbed by organisms, and it is also withdrawn from the atmosphere by minerals. Indeed, this element now forms about one-half of the crust of the earth.

Carbon dioxide is produced by animals, volcanoes and some springs. It is absorbed by plants, which may convert it into peat and coal; and some animals and plants secrete it as $CaCO_3$ to form their hard parts. It has been estimated that the CO_2 now locked up in limestones and other carbonates exceeds 200 times the volume of the entire atmosphere.

Both carbon dioxide and water vapour have an important effect on climate. They act like blankets, or the glass of a greenhouse, transmitting the sun's rays and checking loss of heat into space. Variations in the proportion of these gases present in the atmosphere may have had considerable effect on climate in the past.

Without entering into meteorology and the cause of winds, we will merely note that an exceptionally warm region, like Spain in summer, is generally a cyclonic area with winds blowing in toward the centre; but a cold area

such as an ice-cap is anti-cyclonic, with blizzards blowing outward from it. The geological work of winds is partly indirect, causing waves and conveying vapour from the ocean to fall as rain or snow, and so helping to maintain rivers, glaciers, and all life on land. The direct work includes wind erosion, transport, and the deposition of sand-dunes, loess, etc.

The destructive effect of wind is largely prevented in this country by the vegetation that protects the soil. Desert areas are formed wherever there is no vegetation, whether through drought, excessive trampling, as at Aldershot, or goats, which nibble off every green shoot. In such areas dust and sand grains are blown by the wind and form a natural sand-blast. The rocky walls of canyons are worn, polished, and undercut by this sand-blast, and telegraph poles in deserts are quickly cut through. The chines of the Isle of Wight show the effect of wind erosion, and so do the High Rocks and the Toad Rock near Tunbridge Wells and the Hemlock Stone near Nottingham. In Egypt the Sphinx has a wind-cut hollow in the neck, formed when it was half buried in the sand.

In Leicestershire the granite of Mount Sorrel was similarly grooved by sand-blasts that swirled over the Triassic desert, and the grooves have been covered up by Keuper Marls and preserved to the present day.

Stones lying on the desert floor are bevelled by the sand-blast coming from one direction. If the prevalent wind changes, or the stone is shifted by a passing animal, another facet is cut. These faceted pebbles, or dreikanter (=three edges), are common in desert regions and also in the English Triassic deposits. In some the three edges are parallel, in others they meet in a point, and other less symmetrical forms occur.

Sand grains trundled along the ground by wind become well rounded, to a degree not reached by wave action; and these spherical or millet seed sands are typical of modern and ancient desert deposits.

Many rocks have minute differences in the degree of cementation, and these invisible differences are brought out

by wind erosion in the form of honey-comb weathering. Wind-blown spray may have a similar effect to wind-blown sand.

The constructive work of the wind is seen in the æolian deposits (named from Æolus, god of the winds). Sand-dunes occur in many desert regions and also on low coast lines, where sand grains and shell fragments are blown inland from the fore-shore. A dune may be started by a stump or a stone and grow to a large size, showing a gentle ripple-

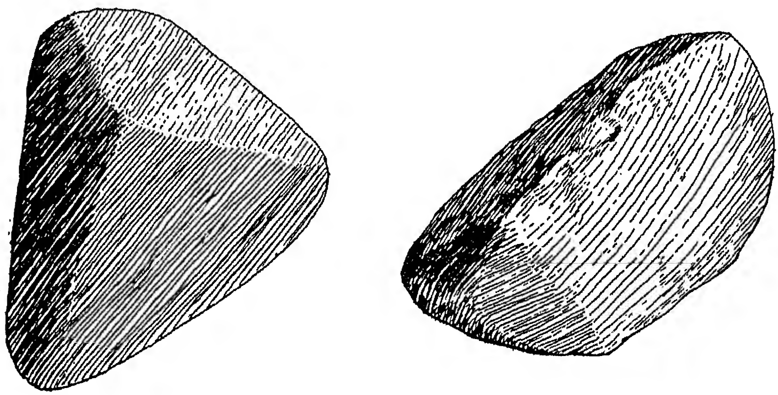

FIG. 140. Dreikanter.

marked slope toward the wind and a steep lee slope which is at the angle of rest for the sand, 20° to 25°, and sometimes even higher. In plan, dunes are commonly crescentic, with the horns pointing down wind, and in section they may show dune bedding, parallel to the forward slope. But the ideal form may be lost, through variable winds or other reasons.

Dunes tend to migrate, sand on the windward slope being continually driven forward on to the steep slope to leeward. Churches have been overwhelmed by sand-dunes in Cornwall and Norfolk, and forests in Moray. The dunes may be bound by suitable plants, after which conifers may be planted on them, as has been done in the Landes of Gascony.

Over large areas of China, in the Mississippi and Rhine valleys, and elsewhere, there are deposits of yellowish loam known as loess, a German word meaning loose. This is unbedded and formed of fine angular fragments, and sometimes contains land shells. Calcareous concretions are common in it (*Loesskindchen*). Loess occurs at irregular heights above the rivers and was clearly not deposited by them. It

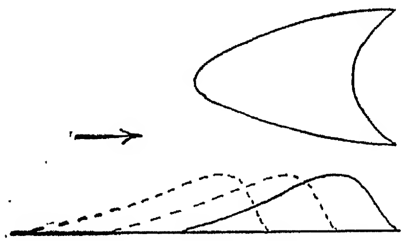

FIG. 141. Sand-Dune, in plan and section.

shows narrow vertical tubes formed about reeds or grasses, and these enable it to stand up in nearly vertical cliffs in spite of its soft nature. It is a wind-blown dust caught by grass stems, formed in a dry period by blizzards blowing outward from the waning ice-sheets. In this country the climate was generally too moist for loess to form, though it has been recorded on the Durham coast; but we have a few patches of brick-earth of æolian origin.

CHAPTER XXI

HEAT AND FROST

IN temperate and moist climates the solid rocks are usually protected by vegetation from direct atmospheric action, though rain penetrates to them. But where rocks are exposed at the surface they are subject to the action of heat and cold, and possibly frost.

The daily range of temperature may well be 50° F. or more, and the annual range may exceed 100° F. This refers to air temperatures, and rocks are often very much hotter than the air, especially where they are dark-coloured and absorb much of the sun's radiation. Granite has a coefficient of linear expansion of .000008, which means that a mass of granite 100 yards long expands about one inch for a rise of 50° F. in its temperature.

Rocks are bad conductors of heat, and so the daily expansion is limited to an outer skin. Below this the stresses due to alternate expansion and contraction induce rupture parallel to the surface, with exfoliation, so that in arid and semi-arid tropical regions rounded rock masses and onion structure are common features. But transverse fractures may be more prominent than those parallel to the surface, and the onion structure is then lost.

Angular blocks are thus strewn about the base of rocks subject to insolation (exposure to the sun), and form a talus or scree beneath precipices in desert regions. They are themselves subject to further disintegration in the same way and may be broken down to their constituent mineral grains before they are covered up and protected by further falls. At this stage the different coefficients of expansion of different minerals may be important, exerting stresses between the grains; and even the same mineral may expand differently in different directions. Quartz, for example, expands twice as much in directions at right angles to the vertical axis as along it, so that a sphere of quartz becomes oblate at higher temperatures and prolate at lower.

This shattering of rocks by heat has been applied to mining and quarrying. In Bangalore slabs of gneiss are obtained by building a fire and pushing it over the rock surface, so leading the plane of separation forward. And in other parts of India shaft sinking was effected by making a fire and then suddenly cooling the heated rock with water. Even in modern mining practice batteries of blow-lamps have been used to shatter quartzose rocks and at the same time render them more easily crushed in the stamp mill.

A small range of temperature variation is effective if it includes the freezing point, and if there is moisture in the rocks. Water in the joints expands on freezing, widening the joints and finally detaching blocks. In a chalk pit or railway cutting after a frosty night one may hear a constant rattle as fragments fall, released by thaw. Many mountain summits are littered with frost-shattered blocks, and extensive screes are formed beneath precipices, which may be cut back to arêtes, or cribs as they are called in Wales.

Frost in soils separates and pulverises the particles, giving a good tilth. The whole surface is raised by the expansion of freezing water, and sometimes columns of ice an inch or more long may be seen beneath the surface soil. On slopes the soil is raised at right angles to the surface, but it falls back vertically on thawing, and thus frost and thaw help in the downward creep of soil.

Seasonal changes of temperature produce deep freezing, but they are less effective than daily frost and thaw, superficial though these may be. In general, slopes exposed to direct insolation show the greatest frost effect, because they have a daily thaw. But if the rocks are dry there will be no freezing. Frost action is pronounced below névé and on the edge of a snow-field, where water comes from the melting snow by day and freezes at night. This process of erosion below a snow-field is called nivation.

Where there has been deep freezing, the surface soil and its snow cover melt while the lower layers are still frozen and impermeable. Solifluction or soil creep is then accelerated, and sheets of sludge descend into the valleys, forming taele gravels. In Chalk areas the chalk rubble known as coombe rock was formed in this way.

CHAPTER XXII

RAIN

LEAVING meteorologists to discuss the causes of rainfall, we need only observe that it requires a supply of humid air and a fall in temperature to below saturation point. This may be due to encounter with colder air or with mountains or hills, which cause the moist air to ascend, expand and cool. The annual rainfall, therefore, is heavier in the west of Great Britain than in the east, and on the North Downs than in the London Basin.

The work of rain is partly mechanical and partly chemical. The mere impact of raindrops loosens particles of soil, and these are carried along in runnels, sometimes directly into streams. The effect of rain may be seen in the garden—the finer particles are carried off the crown of a gravel path into the gutter, while the lawn appears to be unaffected. A short heavy rainstorm does more damage than a long-continued drizzle.

On railway cuttings in clay, gullies may be eroded by rain before grass grows over and protects them; and on steep slopes, such as the sides of Chalk valleys, the soil is washed downhill by the rain as fast as it forms. Hollow lanes are seen on many hillsides, eroded by a combination of rain and traffic. The felling of forests is often followed by great erosion of the soil, and arable lands are ruined, as has happened in Spain and northern China.

Factors favouring pluvial or rain erosion include a copious rainfall at certain seasons, not evenly distributed throughout the year; absence of protective vegetation; and slope of the land. Hence we have the paradox that it is in arid regions that pluvial erosion is most marked. Vegetation is scanty there, and such rain as falls is violent. In South America a railway was carried across a valley on an embankment, and no culvert was provided as rain had never been known in

the area. But after some years rain fell in torrents; the water was held up for a time by the embankment, but that stretch of line was soon literally a wash-out.

Stones may be concentrated at the surface by the washing away of finer particles. In the boulder clay of Swiss valleys rain erosion has produced earth-pillars, each capped by a boulder which has acted as an umbrella, protecting the clay

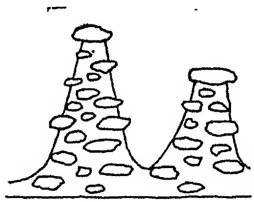

FIG. 142. Earth-Pillars.

below it from erosion, for a time. Similar earth-pillars occur in the Old Red Sandstone conglomerate at Fochabers, Moray.

The sarsen stones that lie on the Chalk Downs near Marlborough and elsewhere are masses of silicified sand from the Eocene. Rain has carried away all the loose sands and clays

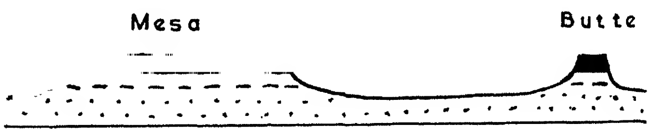

FIG. 143. Mesa and Butte.

that lay around and beneath them, while the sarsens have settled down vertically on to the Chalk.

A thin limestone between clays or sands may form a marked escarpment through the rapid erosion of the underlying bed, while the bed above is swept away from the dip-slope. The Cornbrash and the bands of "marble" in the Weald Clay illustrate this. In horizontal strata a hard bed such as a lava flow often protects the underlying beds from

erosion and forms a steep-sided mesa or tableland, which may be reduced to smaller steep hills called buttes in America and kopjes in South Africa.

Soil is constantly being washed away and carried seaward, but it is renewed from below. Even on flat lands under grass the process is not absolutely inhibited, for earthworms,

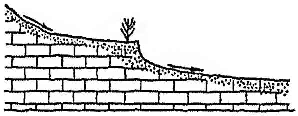

FIG. 144. Cultivation Terrace.

moles and rabbits bring the subsoil to the surface, where it may be distributed by rain and wind. On hillsides there is a decided downward creep of the soil, aided in part by frost and thaw, but more by rain and always by gravity. On sloping arable land some of the loosened soil is washed down to

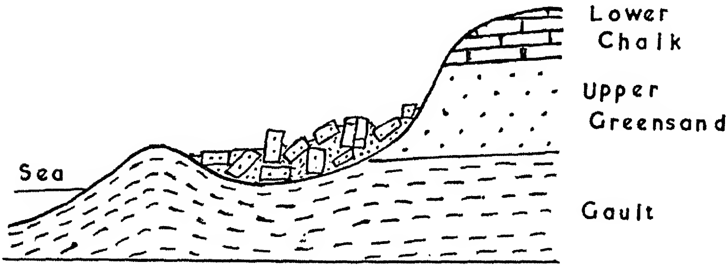

FIG. 145. Landslip, Isle of Wight.

the lower boundary of each field, while it is washed away from the upper part of the field next below; so that in the course of years a terrace is built up and a bank excavated. The result is a lynchet or cultivation terrace. On some hillsides a succession of lynchets may be seen, as at Worth Matravers in Dorset and on the Chalk outlier near Cheddington, Bucks. Some of these are so narrow and the banks

so high that they seem to have been cut for some purpose by early cultivators.

Landslips are sometimes produced by earthquakes, waves and frost, but they are commonly due to rain. Ideal conditions occur in the undercliff east and west of Ventnor in the Isle of Wight, where permeable Lower Chalk and Upper Greensand rest on Gault clay dipping gently seaward. Rain water passing through the Greensand softens and lubricates the Gault, and from time to time masses of rock fall or slide forward ridging up the clay and leaving a lofty cliff of Greensand overlooking a tumble of blocks of all sizes. The Dorset cliffs also show many landslips, due in part to undercutting by the waves. In clay cliffs there is often a semicircular scar behind the landslip and a concave surface down which

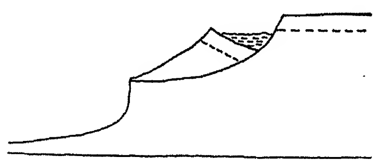

FIG. 146. Landslip in Clay Cliffs.

the mass has slipped, tilting inland as it moved and often holding up water; while a mixture of clay and water flows down gullies as mud-glaciers. In arid regions clays are firm, competent rocks, and it is only when saturated with rain that they yield readily to loads and give rise to landslips and the superficial folds mentioned on page 80.

Avalanches are a type of landslip in which snow supplies much of the falling material and thaw is the starting mechanism, the prime mover being, as always, the force of gravity.

The chemical action of rain is more varied. Rain is by no means pure water. The first drops to fall contain solids, dust and organic matter; and the fine red dust blown from desert regions may give rise to blood rain, to the alarm of the superstitious.

There are always gases dissolved in the rain. They are in the proportion of N 64, O 34, and CO_2 2 *per cent.*, which depends on the relative solubility of the gases as well as their proportions in the atmosphere. Near towns there may be nitric acid, sulphuric acid and ammonia, while salt is present near the sea. And as soon as it reaches the earth, rain takes up other impurities from the soil, increasing its CO_2 and organic matter.

Rain thus becomes a dilute chemical reagent, capable of acting slowly on many minerals and promoting hydration, solution, oxidation and reduction.

A. *Hydration.* (1) Anhydrite + water = gypsum.

$$CaSO_4 \quad 2H_2O \quad CaSO_4.2H_2O$$

This change involves an increase in volume of about 33 *per cent.*, which often causes shattering of surrounding rocks and sometimes local uplift and crumpling.

(2) Olivine + water = serpentine + magnetite.

$$(Mg, Fe)_2SiO_4 \quad Mg_3Si_2H_4O_9 \quad Fe_3O_4$$

This also involves an increase in volume.

(3) Hæmatite and magnetite become limonite.

$$Fe_2O_3 \quad Fe_3O_4 \quad H_6Fe_4O_9$$

B. Solution. Some minerals, such as salt and gypsum, are soluble in pure water. The magnesian limestones of Germany and North-East England contained beds and lenticles of anhydrite and rock-salt. They were first shattered by hydration of the anhydrite and further disintegrated by solution of salt and gypsum.

With CO_2 in solution rain can attack carbonates and form soluble bicarbonates.

Calcite + water + carbon dioxide = calcium bicarbonate.

$$CaCO_3 \quad H_2O \quad CO_2 \quad H_2Ca(CO_3)_2$$

Thus limestones are removed in solution and only their insoluble impurities are left—flints and a little clay from the Chalk, and so on. Joints in limestones are enlarged by solution, and in the Pennines there are areas of bare limestone traversed by widened joints, down which the insoluble matter is washed instead of forming soil. The term karst is applied to such areas, from the region near the head of the Adriatic. There may also be open sinks or swallets, such as

Hull Pot or Gaping Ghyll, communicating with extensive caverns, all formed by solution of limestone. The carbonate may be precipitated again as stalagmite covering the floor or stalactites pendent from the roof of caverns.

In the Chalk no such caverns are formed but the overlying sands or gravels are washed into the solution cavities as they develop, forming pipes. In magnesian limestones the $CaCO_3$ is removed preferentially, giving a cavernous rock with rhombohedra of dolomite, $CaMg(CO_3)_2$.

The action of rain on silicates may be exemplified by the case of orthoclase,

$$\underset{2KAlSi_3O_8}{\text{Orthoclase}} + \underset{2H_2O}{\text{water}} + \underset{CO_2}{\text{carbon dioxide}} =$$

$$\underset{H_4Al_2Si_2O_9}{\text{kaolinite}} + \underset{4SiO_2}{\text{quartz}} + \underset{K_2CO_3}{\text{potassium carbonate.}}$$

Here the soluble potassium carbonate is a valuable source of soil fertility. Crystalline kaolinite is rare and other clay minerals may take its place.

C. Oxidation. Ferrous compounds in hornblende, augite, etc., are oxidised and hydrated, and rocks containing these minerals weather to rusty red or yellow products. Sulphides become sulphates, and then oxides or hydrates.

$$\underset{FeS_2}{\text{Pyrite}} + \underset{H_2O}{\text{water}} + \underset{O}{\text{oxygen}} = \underset{FeSO_4.7H_2O}{\text{melanterite.}}$$

That is the fate of pyritised fossils in moist air. But melanterite is soluble and often passes into limonite while the SO_3 unites with calcite to form selenite crystals, $CaSO_4.2H_2O$.

D. Reduction. It is the organic matter in the soil that may make rain a deoxidising agent. The hæmatite or limonite colouring red sandstones is reduced to ferrous compounds which are carried away in solution, as carbonates or organic salts. In many sand pits the top part is seen to be white, while vertical white lines show where rain has leached out the colouring ferric oxide around roots.

Sulphates may be reduced to sulphides. Thus gypsum is reduced to the unstable calcium sulphide, which gives calcite and sulphur. The association of limestone and sulphur in Sicily is formed in this way.

Chemical action due to rain water is most pronounced in the vadose zone, from the surface down to water level. Of the rain that reaches the earth's surface, some is evaporated, some runs off as surface drainage, and the remainder enters the unsaturated vadose zone. Here a portion returns to the surface through capillarity or through vegetation, another portion is held chemically or physically, and the rest descends to the saturation level, which may fluctuate widely according to rainfall, giving a zone of intermittent saturation. Here again some is held in chemical combination and the rest travels slowly, under the influence of gravity, tending to

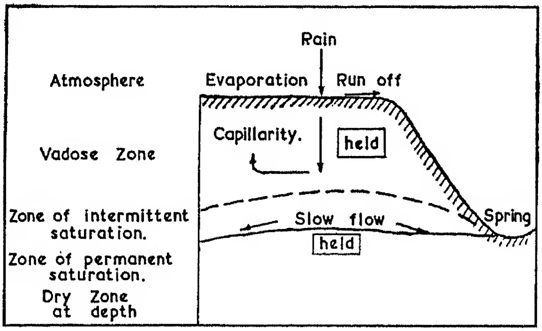

FIG. 147. Ground Water Diagram.

flatten out the water table and sometimes reaching the surface at a lower level in the form of springs. The phreatic zone of permanent saturation extends downward until rock pressure is great enough to close all fissures. The deepest mines are dry.

In moist tropical regions chemical action is increased, owing to heat and abundant vegetation. In Malaya, for example, granite, slate and quartzite are so decomposed, to a depth of one hundred feet or more, as to be readily dug by a spade or quarried by the jet of water from a monitor. Alkali carbonates from felspars attack silica and silicates and remove them as soluble alkali silicates. Iron and manganese are dissolved as carbonates, and these impregnate rocks in tropical rivers, giving them a black coating.

The vegetation also reduces the amount of nitrates and sulphates in solution in tropical rivers. Carbonates of lime and magnesia are slightly less than in temperate lands, owing to the reduced solubility of CO_2 in the warmer water.

PERCENTAGE COMPOSITION OF MATERIALS DISSOLVED IN THE RIVERS OF EUROPE AND AFRICA

	Europe	*Africa*
SiO_2	8.70	17.89
SO_3	9.98	7.22
N_2O_5	.81	.51
CO_2	29.32	23.91
FeO	2.16	4.97
MgO	3.92	4.70
CaO	32.47	26.60
K_2O	3.31	2.83
Na_2O	2.82	1.66
NaCl	5.67	9.33
	99.16	99.62

Even in arid climates chemical action is not at a standstill. Ground water rises to the surface by capillarity and evaporates there, forming concentrated solutions. Hygroscopic salts steal moisture from the atmosphere at night, when saturation point is nearly reached, especially in sheltered places, in hollows or at the foot of a cliff. This may result in deeply corroded material behind a skin of sound rock.

Ground water, besides being a solvent, may deposit material. In arid regions water rises to the surface and evaporates there, throwing down efflorescences of sodium sulphate, sodium carbonate and sodium chloride. Magnesium sulphate and gypsum are sometimes formed, the latter in the rosettes known as desert roses. Hæmatite is also deposited, giving a red colour to many deserts, both contemporary and fossil (Old Red Sandstone, etc.). Silica is another substance deposited from ground water, and this with hæmatite forms desert jasper. Many stones in the desert show concentric banding due to this jasperisation.

Another type of deposition from ground water is seen in the nodules of iron and manganese oxides formed in the residual deposits where limestones have been dissolved. It may be that the hæmatites of Cumberland are also due to

water descending through red Triassic sands and attacking the underlying limestone, replacing it by hæmatite.

Many of the reactions of water in the rocks may be due to magmatic water and not to rain. This is more potent, being highly charged with CO_2 as well as silica. Certainly the commercial deposits of kaolin are formed by magmatic water, for they are often overlain by sound rock.

Weathering residues include soils and subsoils, clay-with-flints, laterite and bauxite. These have been described in Chapter V.

CHAPTER XXIII

INTRODUCTION TO STRATIGRAPHY

IN deciphering the geological history of an area we must first discover where the story starts, and not mistake the last volume for the first. Some scripts run from right to left and some from top to bottom, but earth history is written from below upward. No country possesses a complete edition; there are many and great gaps; but by collating one copy with another we may get a fairly complete account. The fundamental law of superposition, that in undisturbed strata

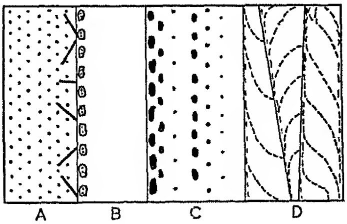

FIG. 148. Vertical Strata: Which is the oldest?
A has a bored surface and yields pebbles to B. C shows graded bedding and D current bedding.

each layer is younger than the bed below and older than the overlying bed, is mere common sense. An igneous rock, however, may be intrusive and younger than the bed above it.

But if subsequent movement has tilted the strata through more than 90°, older beds will overlie younger ones, and thrust faulting may have a like effect. In the absence of recognisable fossils it may not be easy to say which was originally the top of a series and which the bottom. If pebbles of bed A are found in B, then clearly A must be older than B. Borings by worms or molluscs, ripple marks, sun-cracks and rain-prints may indicate which was originally

the upper surface. So may depositional peculiarities like graded bedding and current-bedding. In the former, sand is followed by silt, and silt by mud. Then a fresh access of turbid water repeated the sequence. But if the finest material comes immediately above the coarsest, inversion of the beds is indicated.

Current-bedding (cross or false bedding) is generally seen in shallow-water deposits, where the current carries sand grains over a shoal or sandbank and drops them on the sloping front of the bank, which advances by accretion. The sloping foreset beds merge into the horizontal topset and

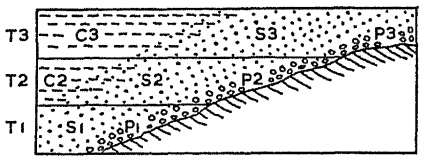

FIG. 149. Diachronism and Facies. The pebble bed P_2 is contemporaneous with the sand S_2 and clay C_2. The time divisions T_1, T_2, T_3 cut across the stratal divisions.

bottomset beds; but a storm or a change of current often erodes the top of the shoal, leaving truncated foreset beds beneath a fresh set of deposits which may show current-bedding in another direction. If the truncated ends are downward the beds have been inverted.

A bed may not be of the same age throughout its extent. Lithological divisions often transgress the time planes. Thus the pebbly base of a series deposited in a transgressive sea may be very much later in one locality than in another. The bed of fine sand between the Upper Lias clays and the Inferior Oolite limestones is earlier in the Cotteswolds than on the Dorset coast. Such deposits are said to be diachronous.

On the other hand, contemporaneous deposits may be of different lithological types and represent different facies, such as terrestrial, littoral and deep-water facies. The marine Devonian is contemporary with the continental and lacustrine Old Red Sandstone, Palæozoic rocks of shallow-water

ERAS	PERIODS. The figures refer to millions of years.	VOLCANIC ACTIVITY.	PRINCIPAL FOLDS with Trends.	VOLCANOES OROGENESIS LAND and SEA
CAINOZOIC	HOLOCENE, PLEISTOCENE, PLIOCENE, MIOCENE. 25		Alpine, E.-W.	Land 4.
	OLIGOCENE EOCENE 35 — 60	West Scotland and Antrim		
MESOZOIC	CRETACEOUS 60 — 120			Marine 3.
	JURASSIC 25 — 145			
	TRIASSIC 25 — 170			
PALÆOZOIC	PERMIAN 40 — 210	Exeter S Scotland	Armorican E.-W. also N.-S.	Land 3.
	CARBONIFEROUS 75 — 285	Scottish Lowlands.		Marine 2.
	DEVONIAN 40 — 325	Scottish Lowlands, Cheviot Devon		Land 2.
	SILURIAN 25 — 350		Caledonian N.E.-S.W.	
	ORDOVICIAN 60 — 410	Borrowdale Snowdon Arenig, etc.		Marine 1.
	CAMBRIAN 90 — 500			
	PRE-CAMBRIAN ? 1000 or more	Wrekin Caer Caradoc Charnwood	Charnian N.W.-S.E.	Land 1.

FIG. 150. Physical History of the British Area.

ERAS	PERIODS.	DOMINANT FORMS OF LIFE.	COMMON FOSSILS.	IMPORTANT EVENTS.
CAINOZOIC	HOLOCENE, PLEISTOCENE, PLIOCENE, MIOCENE.	Mammals	Gastropods	
	OLIGOCENE EOCENE	dominant.	Lamellibranchs	Acme of Nummulites
MESOZOIC	CRETACEOUS	Reptiles	Ammonites Belemnites Terebratulids	Last Ammonites and Belemnites First Angiosperms
	JURASSIC	dominant.	Rhynchonellids Echinoids	First Bird
	TRIASSIC			First Mammal
PALÆOZOIC	PERMIAN	Amphibia dominant.		Last Trilobites
	CARBONIFEROUS	Fishes	Rugose Corals. Crinoids Goniatites Productids Spiriferids	First Reptiles
	DEVONIAN	dominant.		First Amphibia First Goniatites
	SILURIAN			Last Graptolites First Land Plants
	ORDOVICIAN	Invertebrates	Trilobites Graptolites	First Fishes.
	CAMBRIAN	dominant.	Pentamerids Orthids	First well known Marine Fauna.
	PRE - CAMBRIAN		Few organisms preserved.	

FIG. 151. The Development of Forms of Life.

origin, with trilobites and brachiopods, may be of the same age as shales accumulated in deep water, with no fossils other than graptolites.

Geological history is divided into Eras and Periods, just as English history is divided into dynasties and reigns. The Periods are equally convenient units throughout Europe and North America; but if stratigraphy had begun in South Africa, India or Australia, different units would certainly have been chosen. Periods are subdivided into Epochs, and Epochs into Ages. The rocks deposited during a Period are called a System, and the other time-divisions have corresponding rock-divisions, as below.

Time divisions	*Stratal divisions*	*Examples*
Era	Group	Mesozoic
Period	System	Cretaceous
Epoch	Series	Chalk
Age	Stage	Senonian (Upper Chalk)
(Epibole)	Zone	*Micraster coranguinum*

The smallest stratal subdivision is the zone, including all the rocks in which a certain assemblage of fossils occurs. It is named after one of them; but the zone can be identified in the absence of the name-fossil and is not co-extensive with the range of that species. On the other hand, the hemera is a time-division (literally, the day) marked by the acme or greatest abundance of a single species. S. S. Buckman established a vast number of ammonite hemeræ in the Jurassic Period; most of them are of only local significance.

The names of the Eras and Periods have been given in Chapter III. Some of the principal physical events in the British area are tabulated on page 187, and the development of forms of life on page 188.

FURTHER READING

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The REGIONAL GEOLOGIES issued by the Geological Survey are very useful as guides to local geology.

CHAPTER XXIV

FOSSILS

It is in fossils that we find the surest guide to the age of a rock. For more than 500 million years life has been evolving new forms, under the stimulus of changing conditions or in order to attain fresh habitats where the competition is less strenuous. The burrowing *Lingula* has persisted with little change from the Cambrian to the present day; but most genera have a much shorter life. Species, and associations of species, may characterise still smaller fractions of geological

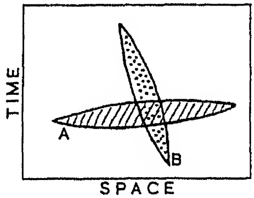

FIG. 152. Range of two Species in Time and Space. Species A is a more useful time indicator than B.

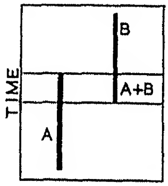

FIG. 153. The Association of two Species defines a narrower zone than either species alone.

history and be limited to a few feet or inches of rock; and if such species have a wide geographical range they are most valuable time-markers. Marine floating or swimming organisms have more chance of wide distribution than forms confined to fresh or shallow waters, and the graptolites of the Lower Palæozoic and the ammonites of the Mesozoic have proved most useful in zoning those groups, that is, in correlating rocks of the same age irrespective of their lithological characters. In some cases variations within a single species

may enable one to determine the horizon, as in the Chalk sea-urchins *Micraster* and *Echinocorys*.

But many species and genera are confined to a narrow range of habitat. They are facies fossils. In the Oligocene Beds of the Isle of Wight, for example, certain groups of fossils recur time after time, whenever the conditions were suited to them, freshwater, brackish or marine. On the northern shores of the Island many of these Oligocene shells lie side by side with modern species; and if both are entombed together they will become derived (or *remanié*) and contemporaneous fossils respectively, two groups that must always be distinguished to avoid misleading results.

Few recognisable fossils occur in beds older than the Cambrian; but the earliest Cambrian faunas contain representatives of many phyla and may well be the result of as long a period of evolution as from the Cambrian to the present time. Not all the Pre-Cambrian rocks are ill-fitted for the preservation of fossils, and their general absence must be attributed to the hard parts of the earlier forms being unstable, perhaps organic matter instead of calcareous. But the early seas were not destitute of lime, for thick masses of limestone occur in the Pre-Cambrian rocks: in eastern Canada the Grenville Limestone appears to be 50,000 feet thick.

The Animal Kingdom is divided into a number of phyla (or races, such as the Mollusca or the Vertebrata). Each phylum is divided into classes (Gastropoda, Mammalia), each class into orders (Pulmonata, Carnivora), each order into families (Helicidæ, Canidæ), each family into genera (*Helix, Canis*), and each genus into species (*Helix aspersa, Canis familiaris,* or snail and dog). A species includes all the individuals that are sufficiently alike to be conveniently referred to under the same name; and a genus should include a number of species all descended from the same immediate ancestral stock. Since, however, the ancestry is not obvious, many genera have been established to include species having certain features in common. These morphological genera may be abandoned as knowledge increases; and many of the older genera had an unwieldy number of species and have had to be divided.

A generic name is always treated as a Latin noun, and the name of a species is either a Latin* adjective, agreeing in gender with the generic name; or a noun in apposition, which need not agree; or a noun in the genitive case. Like all foreign words, both should be italicised, the former with a capital letter and the latter without. Finally, to avoid any ambiguity, the name of the person who first described and named the species is given, in full or contracted; it is put in brackets if the generic name has since been changed. Thus, the common Whitby "snake-stone," named by Sowerby, was originally called *Ammonites communis* Sow. It is now *Dactylioceras commune* (Sow.), the ammonites being far too numerous for a single genus. Beginners may, however, well omit the author's name.

A brief sketch of the history of the various groups of plants and animals will now be attempted.

PLANTS. These must have preceded animal life; and land plants must have preceded land animals.

The unicellular diatoms, encased in thin walls of opaline silica, form the diatomaceous oozes of the ocean floor and diatomite or kieselguhr on old lake bottoms. They are known from Jurassic and later rocks. The Algæ are recorded from the Pre-Cambrian upward, but many so-called fucoids are merely markings of inorganic origin. *Halimela* and *Lithothamnion* are important lime-secreting algæ; and *Chara* is known by its spirally marked calcareous spore cases from the Oligocene of the Isle of Wight and other freshwater deposits.

Land plants date from the end of the Silurian, and ferns, horsetails and club-mosses are the chief forms from the Old Red Sandstone and the Coal Measures. Cycads dominate the Mesozoic floras, with ferns and conifers, and Angiosperms are not known before the Cretaceous. The maidenhair tree, *Ginkgo,* is a very ancient genus, ranging from the Permian to the present day.

* In the time of Linnæus, founder of the binomial system, Latin was still a universal language; and it was not the scientists but the classical pedants who killed it. It is pronounced like English, as it is in legal and medical terms.

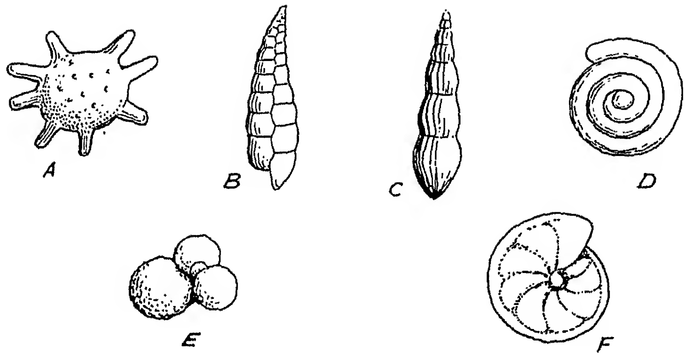

FIG. 154. Foraminifera.

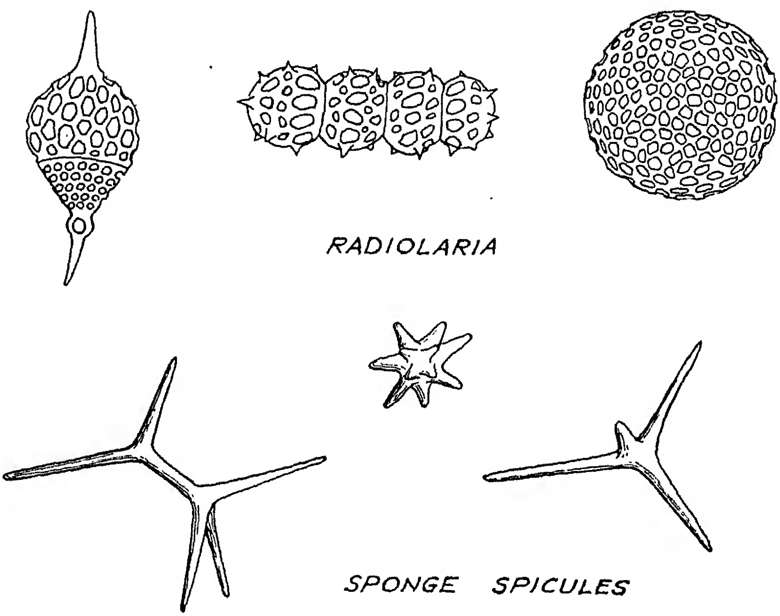

FIG. 155. Radiolaria and Sponge Spicules. (Siliceous Remains.)

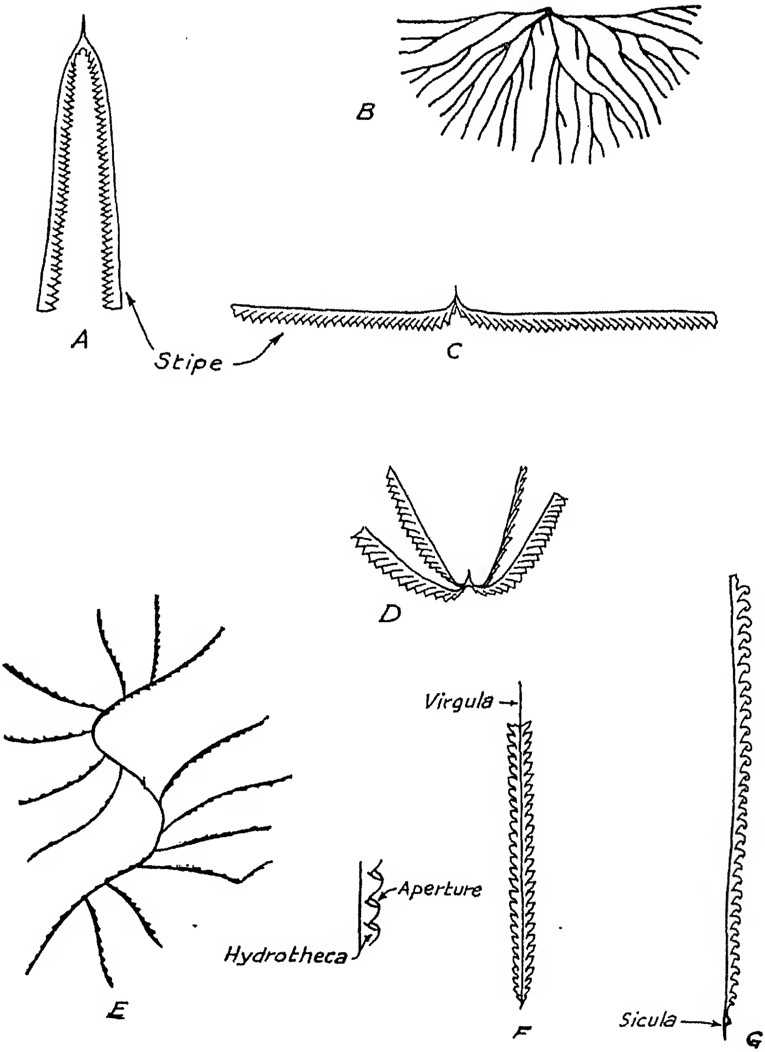

FIG. 156. Graptolites.
A and C—*Didymograptus*. B—*Dictyonema*. D—*Tetragraptus*. E—*Nemagraptus*. F—*Glyptograptus*. G—*Monograptus*.

PROTOZOA. The foraminifera are usually very small, but their calcareous tests may make important contributions to limestones, and *Globigerina* ooze is a widespread deposit on the ocean floors. *Saccamina* gives a spotted appearance to some bands of the Carboniferous Limestone. The coin-like *Nummulites* is of zonal value in the Eocene and Oligocene, and a species two inches in diameter occurs in the

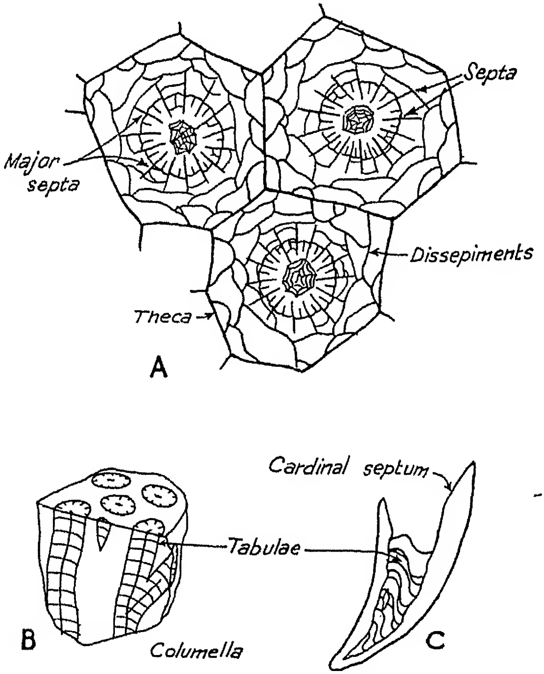

FIG. 157. Corals.
A—*Lonsdaleia*. B—*Lithostrotion*. C—*Zaphrentis*.

nummulitic limestone of Egypt. Siliceous tests of Radiolaria are abundant in some oceanic oozes.

PORIFERA. The sponges are known by their siliceous or calcareous spicules, and also by their form. *Ventriculites* is often seen in flints from the Chalk, and *Rhaphidonema* is abundant in the Lower Greensand of Faringdon in Berkshire.

THE CŒLENTERATA, familiar in the sea-anemones and jelly-fish, have a mouth, which may be surrounded by tentacles, and a simple body-cavity in which food is digested. Some are colonial organisms, like the graptolites of Lower Palæozoic times, in which a row of little cups (thecæ), each housing a polyp, lay on one or both sides of an axis, the virgula. *Dictyonema* is a net-like form from the top of the Cambrian; *Didymograptus* (Ordovician) has two branches or stipes, each with a single row of thecæ; *Diplograptus* a single stipe with thecæ on both side; and *Monograptus* (Silurian) a single stipe with one row of thecæ only. We do not know what the soft parts were like; and it is possible that the graptolites should be placed in a higher group.

The coral polyp is like a sea-anemone fitted with a calcareous cup (corallite), with radiate septa which may or may not unite in the centre to form a rod-like columella. The larval form is free-swimming, which facilitates distribution, and there is also reproduction by budding, which gives large colonies of various shapes. The Rugose corals of Palæozoic age had two primary septa instead of six as in modern forms.

Heliolites and *Halysites* (the chain coral) are common in Silurian limestones; *Favosites* and the slipper-shaped operculate *Calceola* in the Devonian. The Carboniferous Limestone is rich in corals, including the simple *Zaphrentis* and *Caninia* and compound forms like *Lithostrotion, Lonsdaleia* and *Cyathophyllum*. In the Jurassic *Isastræa* and *Thamnasteria* occur.

VERMES. Worm borings and casts are known from Pre-Cambrian rocks onward, and forms secreting calcareous tubes occur in many deposits. *Serpula* and *Spirorbis* date from Lower Palæozoic times, and *Ditrupa* is often abundant at the base of the London Clay.

ECHINODERMATA. These creatures show typically five-rayed symmetry and include the Crinoidea (sea-lilies), Asteroidea (star-fishes), Ophiuroidea (brittle-stars), Echinoidea (sea-urchins), and Holothuroidea (sea-cucumbers), as well as two extinct classes, the Cystidea and the Blastoidea, which are confined to the Palæozoic.

The star-fishes have a mouth in the centre of the under

side of the disk, and the ambulacral grooves beneath the arms are furnished with tube-feet, which are locomotory organs connected with a water-vascular system. The skeleton consists of many calcareous plates, which are not in contact, so that the arms are flexible. Each plate is a light struc-

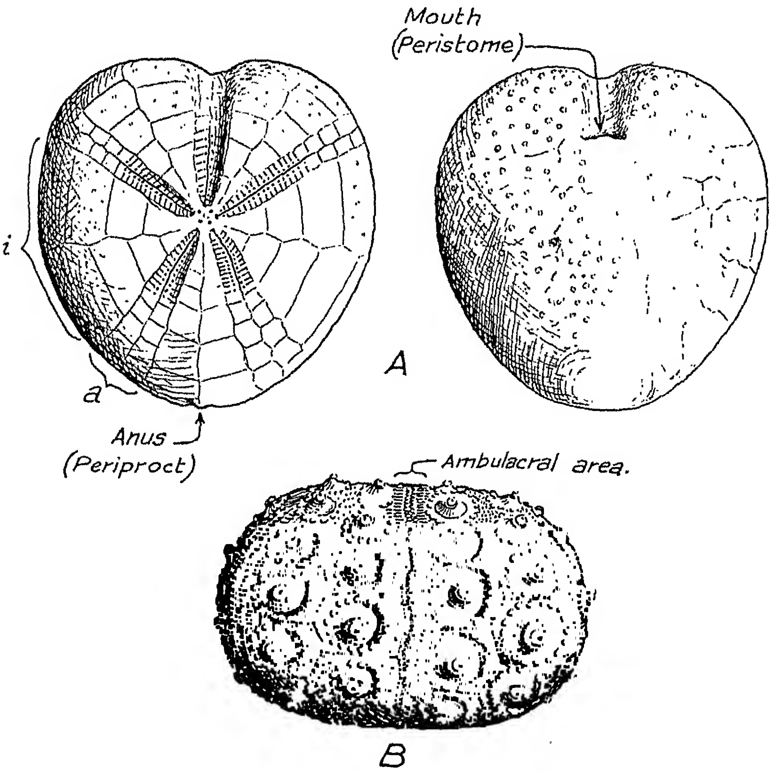

FIG. 158. Echinoids.
A—*Micraster*. B—*Cidaris*. a—ambulacral area. i—interambulacral area.

ture composed of calcite in crystalline continuity; and on fossilisation it behaves like a single crystal and gives the typical calcite cleavage. This feature is common to each element of the skeleton of all the Echinodermata, such as the plates and spines of echinoids and the stem ossicles of

crinoids. *Metopaster* is a star-fish from the Chalk, and *Ophioderma* a brittle-star from the Lias.

The Echinoidea are enclosed in a test which is usually composed of five double rows of plates pierced with pores for the tube-feet (the ambulacral areas), separated by five double rows of larger plates (interambulacral areas). The regular echinoids have the mouth in the centre of the base and the anus at the summit of the test; but in the irregular

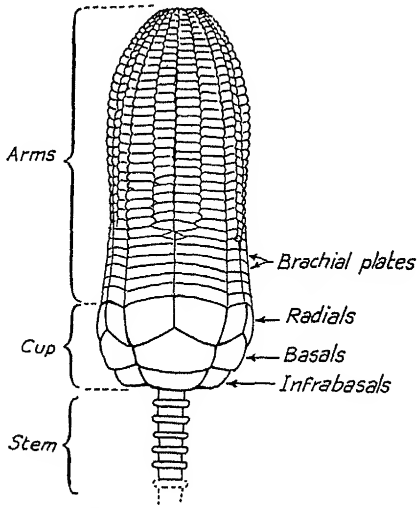

FIG. 159. A Crinoid.
Encrinus.

echinoids the anus is always posterior, between the summit and the base, and the mouth lies between the centre and front of the base. The test is usually covered with spines, which may be very large and attached by a ball-and-socket joint. *Cidaris* (U. Jurassic), *Hemicidaris* (Jur.-Cret.) and *Peltastes* (Jur.-Cret.) are regular echinoids, and the irregular include the shield-like *Clypeus* (Jur.), the heart-shaped *Micraster* (Chalk), *Conulus* and *Echinocorys* (Chalk).

A crinoid may be likened to a star-fish rooted to the sea-floor by a flexible stem. The arms surround the mouth and divide repeatedly. The Jurassic *Pentacrinus* has pentagonal

stem ossicles, but in *Apiocrinus* (Jur.) these are cylindrical and the stem expands toward the top and passes gradually into the calyx.

The Cystidea and Blastoidea usually had short stems. *Pentremites* is a typical bud-like blastoid from the Carboniferous Limestone.

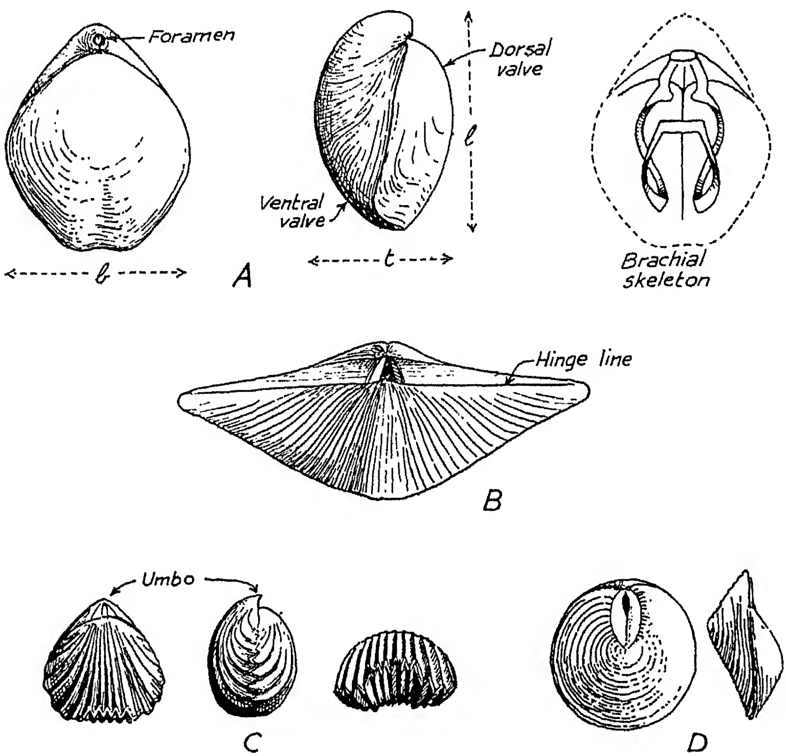

FIG. 160. Brachiopods.
A—*Terebratula*. B—*Spirifer*. C—*Rhynchonella*. D—*Discina*.
b—breadth. l—length. t—thickness.

THE BRACHIOPODA are enclosed in a shell of two valves, dorsal and ventral, of which the ventral is usually larger than the dorsal and has a foramen below the beak (umbo) through which passes a pedicle for attachment to a rock.

The name means "arm-footed," in reference to the spiral "arms" which serve to produce a current of water carrying food to the mouth. They may be supported by a calcareous framework. Adductor and divaricator muscles are attached to the valves on opposite sides of the hinge for closing and opening them.

Brachiopods with imperfect hinge mechanism (Inarticulata) include *Lingula, Discina* and *Crania* (all Cam. or Ord. to Recent). Among the Articulata are *Productus* (Carb.-Perm.), a spinose form with concave dorsal valve; *Leptæna* (Ord.-Carb.), also concavo-convex; *Orthis* (Cam.-Carb.); *Pentamerus* (Sil.-Dev.); *Spirifer* (Sil.-Perm.); *Atrypa* (Ord.-Dev.); *Rhynchonella,* with radial ribs, very abundant in the Jurassic and Cretaceous, as also is *Terebratula,* which has a smooth shell.

THE POLYZOA are colonial animals, as the name implies, and the colonies often resemble plants, an alternative name being Bryozoa or moss animals. The sea-mat, *Flustra,* is among our common "seaweeds." Polyzoa differ from Hydrozoa, which they resemble, in possessing a distinct U-shaped alimentary canal. *Fenestella* is a net-like polyzoon of Palæozoic age, and *Theonoa* is common in the Pliocene Coralline Crag.

MOLLUSCA. The three main classes of Mollusca are the Lamellibranchia or Pelecypoda (oyster, mussel), Gastropoda (whelk, snail), and Cephalopoda (octopus, nautilus).

In bivalved molluscs the valves are right and left, not dorsal and ventral as in the brachiopods. The two valves are commonly alike (equivalve), but the anterior and posterior ends are unlike (inequilateral), while brachiopod shells are inequivalve and equilateral. There are two (or one) adductor muscles which close the valves when they contract; and on their relaxation the valves are opened by an elastic ligament. Their attachment leaves muscle-scars on the inside of the valves, which also show a pallial line, marking the attachment of the mantle (pallium). The pallial line may have an embayment or sinus at the posterior end in burrowing forms that have long siphons to bring water and food. The umbo or beak generally points forward. The hinge is

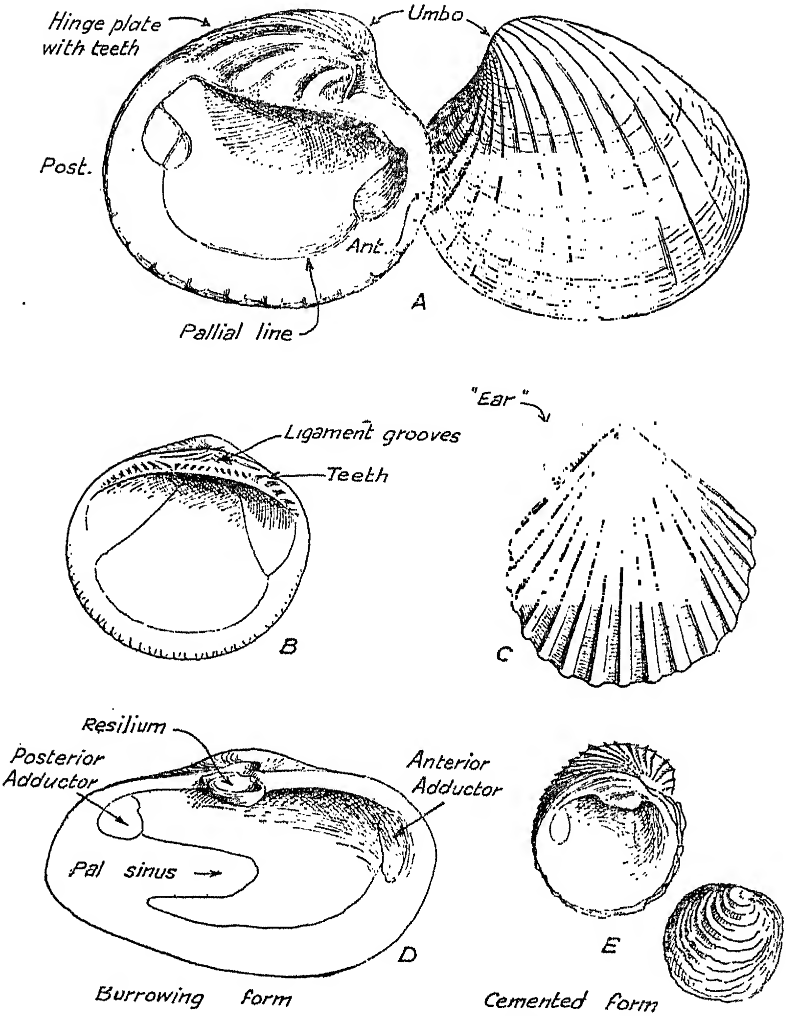

FIG. 161. Lamellibranchs (Pelecypods).
A—*Venericardia.* B—*Pectunculus.* C—*Pecten.* D—*Mya.* E—*Chama.*

strengthened by teeth which fit into sockets in the opposite valve.

Lamellibranchs, like gastropods, are comparatively unimportant in the Palæozoic and are at their acme now.

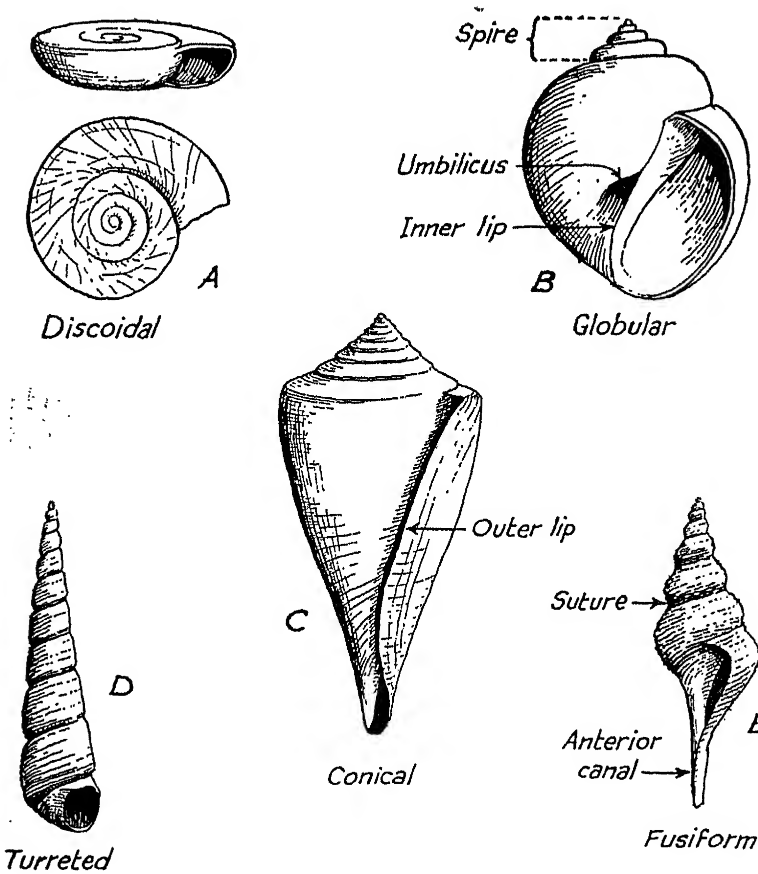

FIG. 162. Gastropods.
A—*Planorbis*. B—*Natica*. C—*Conus*. D—*Turritella*. E—*Fusus*.

Unio is a freshwater mussel and so probably was *Carbonicola* of the Coal Measures. *Cyrena* lives in fresh and brackish waters. The oysters (*Ostrea*) date from the Trias;

highly inequivalve forms are known as *Gryphæa* and those with twisted umbones as *Exogyra*. They are monomyarian,

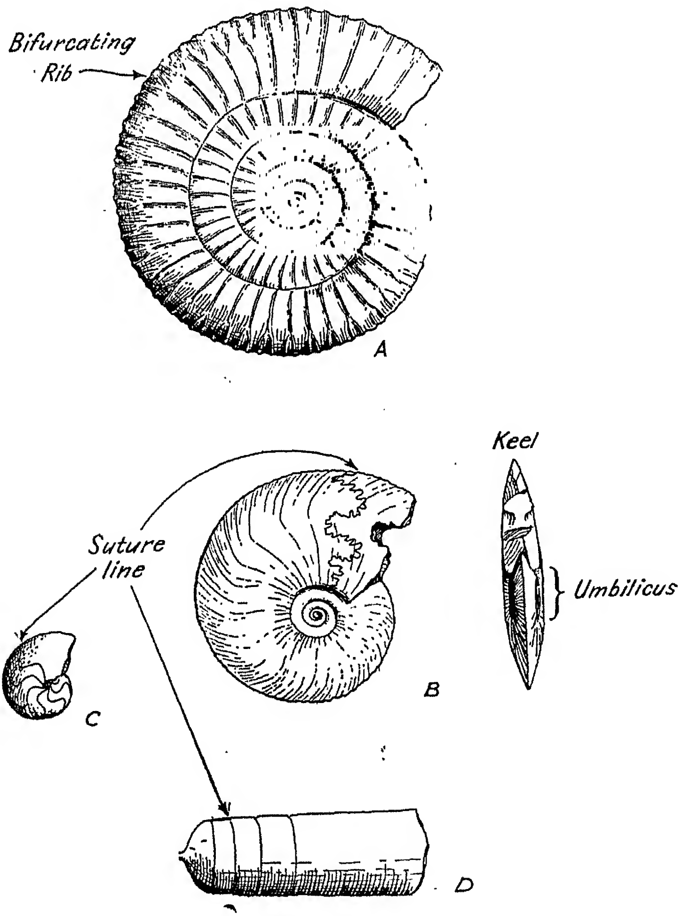

FIG. 163. Cephalopods.
A—*Dactylioceras commune.* B—*Oxynoticeras.* G—*Gephyroceras.* D—*Orthoceras.*

with a single muscle-scar in each valve. *Trigonia,* abundant in the Jurassic and Cretaceous, lingers on in Australian seas. *Pectunculus* (Cainozoic and Recent) has nearly circular

valves. *Pholas* and *Saxicava* bore into rocks, and *Teredo,* the ship-worm, perforates wood.

The gastropods (=stomach-footed) usually have a univalve shell which may be a simple cone, as in the limpet, *Patella,* but which commonly forms a right-handed spiral, or in some cases a left-handed one. The spire may rise well above the body-whorl (*Turritella, Fusus*): in other cases the whorls

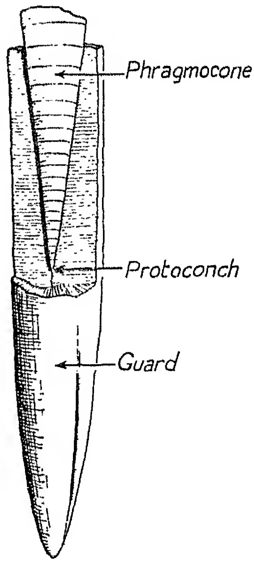

Fig. 164. A Belemnite. Partly in section.

are all in one plane or near it (*Planorbis*). In the cowries, *Cypræa,* the last whorl encloses all the others.

Helix lives on land; *Limnæa, Planorbis* and *Viviparus* (=*Paludina*) are freshwater forms; and *Neritina, Melania* and *Potamides* live in brackish waters. The great majority are marine.

The cephalopods include the squid, cuttle-fish, and *Nautilus,* which are still living, and the extinct ammonites and belemnites. They are entirely marine. The name, meaning "head-footed," refers to the tentacles surrounding the head.

The Nautiloidea were abundant in Palæozoic times, but only one genus survives. This has a chambered shell, the evacuated early portions being sealed off by shelly septa as growth proceeds. The empty gas chambers give buoyancy to the shell, and they are traversed by a central tube, the siphuncle. The shell was straight in the Palæozoic *Orthoceras*, but in *Nautilus* it is coiled in a plane spiral with few whorls.

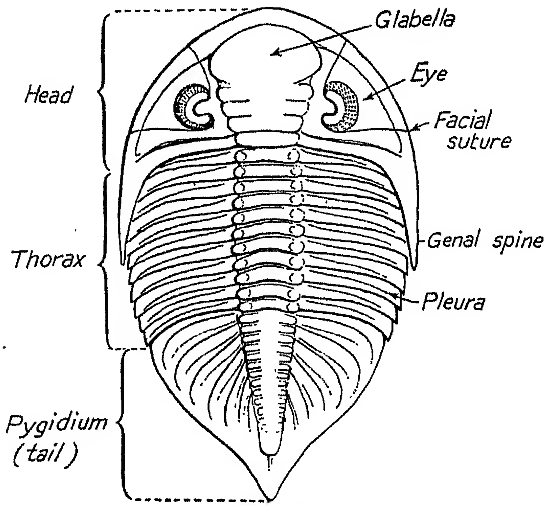

Fig. 165. A Trilobite. *Dalmanites*.

The Ammonoidea also had a chambered shell, but the junction of the septa with the shell was strengthened by folds (lobes and saddles) and further puckered in a very complicated pattern. This suture line is best seen when the outer shell has disappeared. The siphuncle was marginal.

The Devonian and Carboniferous goniatites have angular suture lines. *Amaltheus* and *Hildoceras* are among the very numerous Liassic ammonites; *Parkinsonia* is from the Inferior Oolite; and the Portlandian *Titanites* is a large ammonite two feet or more in diameter. The Gault of Folk-

stone yields *Hoplites* and aberrant forms such as *Hamites*. *Turrilites* has a raised spire.

The Belemnoidea are generally represented only by the pencil-shaped calcareous guard, which was internal like the cuttle-fish "bone." It has a vestigial chambered shell in the hollow at the anterior end. Belemnites are common fossils in most of the Jurassic and Cretaceous rocks.

THE ARTHROPODA (=jointed feet) include the Crustacea, most of which breathe by gills, and the air-breathing Arachnida, Insecta, and other classes.

The trilobites were Palæozoic marine forms of which only the dorsal shield is commonly preserved. This shows a head, a thorax with a number of flexible pleuræ, and a tail or pygidium. The trilobed character is given by two furrows running from front to rear and dividing a raised axial lobe from a lower pleural lobe on either side. Most forms could roll up like wood-lice. The appendages are rarely seen. *Calymene* is a well-known trilobite from the Wenlock Limestone, and species of *Paradoxides* serve as zonal fossils in the Middle Cambrian.

The Ostracoda are minute crustacea possessing a bivalved carapace. *Cypridea* swarms in some Purbeck and Wealden beds.

The Malacostraca include the crabs and lobsters and the isopods. *Meyeria* is found in the "Lobster Bed" at Atherfield, Isle of Wight, and *Palæocorystes* is not uncommon in the Gault.

Insects are known from the Carboniferous onward, and are beautifully preserved in the Baltic amber and in Miocene shales at Oeningen on Lake Constance and Florissant, Colorado. The Arachnida include scorpions and spiders and extinct forms like *Eurypterus* and *Pterygotus* from the Silurian and Old Red Sandstone.

THE FISHES appear first in the Ordovician Harding Sandstone of Colorado. In Europe they are known from the top of the Silurian and are important fossils in the Old Red Sandstone. Here are found the armoured ostracoderms (*Cephalaspis, Pteraspis*), shark-like elasmobranchs, and air-breathing dipnoi or mud-fishes, which could survive the drying up of their pools.

AMPHIBIA appear in the Carboniferous and REPTILIA in the Permian. The marine reptiles, plesiosaurs and ichthyosaurs, lived in Jurassic and Cretaceous seas, and the dinosaurs dominated the lands and the pterosaurs the air in those Periods. Crocodiles and turtles appeared in the Trias, and snakes in the Eocene.

The earliest known BIRD, *Archæopteryx,* is preserved in the Upper Jurassic of Solenhofen in Bavaria. It had a toothed beak and a jointed tail, but it was feathered.

THE MAMMALS started with *Microlestes* in the Rhætic or Lias, but that "little beast" was probably a monotreme or a marsupial. They remained small and scarce throughout the Mesozoic age of reptiles. From Eocene times they multiplied rapidly and in their turn occupied land, sea and air. The cold of the Pleistocene killed off many of them, and they are past their acme, except for Man himself. The gradual reduction in the number of toes, from four in *Eohippus* to one in *Equus,* with increasing size in these horses, and the changes in the tusks and molar teeth of the elephants, give striking examples of evolution and adaptation to special needs.

FURTHER READING

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CHAPTER XXV

PRE-CAMBRIAN

ABSENCE of fossils is of course no proof of Pre-Cambrian age. The best evidence is that the rocks in question are overlain unconformably by beds containing Cambrian fossils, or that they have yielded pebbles to Cambrian conglomerates.

The largest area of Pre-Cambrian rocks in Great Britain is in the Scottish Highlands. In the North-West Highlands and the Outer Hebrides the Lewisian gneiss is

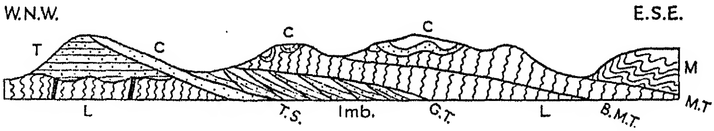

FIG. 166. Pre-Cambrian and Cambrian Rocks of the North-West Highlands of Scotland.
C—Cambrian. T—Torridonian. M—Moine Schists. L—Lewisian Gneiss. T.S.—Sole. G.T.—Glencoul thrust. B.M.T.—Ben More thrust. M.T.—Moine thrust. Imb.—Imbricate structure. Length of section 9 miles.

well metamorphosed; but this in itself is no evidence of age, since Mesozoic and later rocks can be traced laterally into schists in the Alps and elsewhere. Above the Lewisian gneiss are many isolated hills of Torridon Sandstone, and this is covered unconformably by Cambrian rocks. Here the evidence is complete; and the two rock types, one metamorphosed and the other not, are commonly seen in other parts of the world. They have been called Protarchæan and Eparchæan.

The Moine gneisses have been thrust over Cambrian rocks and are probably of Pre-Cambrian age. They cover the greater part of the Highlands, but to the east and south-east

they give place to the Dalradian schists, quartzites and limestones which may possibly represent altered Palæozoic rocks. All we can say for certain is that they are pre-Devonian.

In Anglesey a great thickness of gneisses, schists, quartzites and volcanic rocks, the Mona complex, is covered in places by Ordovician beds. Pebbles derived from it, however, occur in the basal Cambrian conglomerate at Bangor, on the mainland, proving the Pre-Cambrian age.

Between Caernarvon and Bangor acid volcanic rocks occur, with intrusive aplitic granite (*i.e.*, granite without biotite). Near St. David's in Pembrokeshire, too, acid lavas and tuffs, with intrusive rocks, occur in a thick series of sedimentary deposits. Both these occurrences lie beneath Cambrian rocks.

In Shropshire the schist of Rushton, near the Wrekin, appears to be the oldest rock. The Uriconian volcanics, mostly rhyolitic lavas and tuffs, with aplitic granite, form the Wrekin, Caer Caradoc, and other hills along the Church Stretton fault; and very similar rocks occur farther west in Pontesford Hill. Between them the wide moorland of the Longmynd shows a great thickness of slaty rocks and some conglomerates containing Uriconian pebbles. Cambrian rocks overlie the Uriconian.

The Malvern Hills are formed of gneisses and volcanics, which have yielded pebbles to the Cambrian conglomerates. Volcanic rocks are seen near Birmingham (the Lickey Hills) and Nuneaton. Charnwood Forest, near Leicester, shows volcanic tuffs and agglomerates, with intrusive and sedimentary rocks. They are covered by Trias; but Cambrian beds struck in borings near Leicester are without the foliation shown by the Charnian rocks, which are therefore probably older.

There are thus three facies of Pre-Cambrian rocks in Britain :

Sedimentary, as in the Torridonian and Longmyndian,
Volcanic, as in the Uriconian and Charnian,
Gneissic, as in the Lewisian and Malvernian,

besides plutonic and minor intrusions. They occur chiefly

in the north and west, with small inliers in the Midlands. We may tentatively correlate the various acid volcanic rocks, and also the Torridonian with the Longmyndian conglomerates, both of which contain rhyolite pebbles. The Torridon Sandstone lies on a deeply dissected surface of Lewisian gneiss, with peaks 2,000 feet above the valleys, our oldest fossil landscape. It probably accumulated in a lake or inland sea; and the surrounding lands were deserts, for there were no land plants then. The freshness of the felspar grains, red colouring, and occasional wind-cut pebbles, are due to desert conditions. Most of the material came, not from local rocks, but from some area of granitic gneisses to the north-west, the old North Atlantic continent.

The old rocks of Charnwood Forest have an anticlinal structure about a N.W.-S.E. axis, the Charnian strike. The foliation in the Lewisian and Moine gneisses strikes between this and E.-W.

Pre-Cambrian rocks cover very large areas in Canada, Scandinavia, peninsular India and South Africa. In Finland as many as six distinct Systems have been traced in them.

CHAPTER XXVI

LOWER PALÆOZOIC

CAMBRIAN, Ordovician and Silurian rocks occupy most of Wales, the land of the Cymry, the Ordovices and the Silures. They were laid down in a gulf or geosyncline, with subsidiary basins, stretching S.W.-N.E. and including Wales and the border counties, the Lake District, Man, and the Southern Uplands of Scotland. The Cambrian of North-West Scotland belongs to another province.

The deposits were mainly clays, now altered to mudstones, shales or slates, with sandstones and conglomerates formed in shallower water, and occasional impure limestones. The Lower Cambrian is largely arenaceous (Harlech Grits, Comley Sandstone, etc.), and sandy beds are widespread at the top of the Silurian, when the geosyncline had silted up. But throughout most of the three Periods the sea-floor subsided as sedimentation continued, and sandy beds are confined to shallow-water areas on the flanks of the gulf.

The dominant fossils of the Cambrian are trilobites. Fragments of *Olenellus* (*sensu lato*) characterise the Lower Cambrian, the Middle Cambrian has many species of *Paradoxides* which serve as age indicators, and *Olenus* is typical of the Upper Cambrian. All these have large heads and small tails; but in *Agnostus* head and tail are roughly equal in size. New types appear in the Tremadoc Beds, which are really transition beds and included by some in the Ordovician. Brachiopods like *Orthis* and *Lingula* also occur.

The Ordovician shales yield many genera of graptolites—*Didymograptus, Dicranograptus,* etc., while trilobites such as *Trinucleus, Asaphus* and *Ogygia* occur in the sandstones with *Orthis* and other brachiopods.

In the Silurian even more than in the Ordovician there are two markedly different faunas—a graptolitic fauna found in the deep-water shales, and a shelly fauna in the shallow-

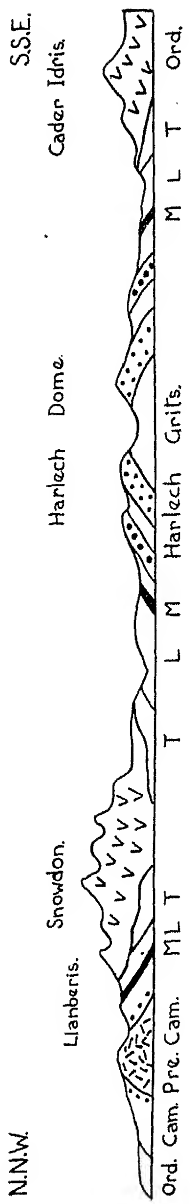

FIG. 167. Structure of North Wales.
V—Ordovician volcanics. Ord.—Ordovician. T—Tremadoc Beds. L—Lingula Flags. M—Menevian Shales.
Length of section 36 miles.

water limestones and sandstones, rich in trilobites (*Calymene, Dalmanites*), brachiopods (*Orthis, Leptæna, Pentamerus, Spirifer*) or corals (*Favosites, Heliolites*). The graptolites are much reduced in genera, mainly *Monograptus, Cyrtograptus* and *Rastrites,* and they die out entirely at the top of the Lower Ludlow. Merostomata (*Eurypterus, Pterygotus*) appear in the Downtonian, and the presence of abundant fish remains in the Ludlow Bone Bed has led some geologists to take that bed as the base of the next System.

THE CAMBRIAN SYSTEM

Tremadoc Beds
Lingula Flags
Menevian Slates
Harlech Grits

The above table shows the sequence in North Wales. In the Harlech dome a series of massive grits, separated by shales, form a barren mountainous area, including Rhinog and Diphwys. The base is not seen. The grits become coarser and thicker toward the south and east, where the land lay, while beyond the Snowdon syncline they are very thin.

To the north, east and south the Harlech Grits are succeeded by the black slates of the Menevian, and then by the Lingula

Flags, in which *Lingulella davisi* is abundant in places. Last come the Tremadoc Beds, in part cut off by the Ordovician overstep.

Near Bethesda, Llanberis and Nantlle excellent roofing slates occur in the Lower Cambrian.

In Pembrokeshire purple sandstones (of which St. David's Cathedral is built), flags and slates are exposed in Caerfai Bay, Solva Harbour and elsewhere. They yield Lower, Middle and Upper Cambrian fossils, but the Tremadoc Beds are generally wanting.

In Shropshire the basal quartzite and conglomerate, lying unconformably on Uriconian rocks, pass up into the glauconitic Comley Sandstone. Calcareous bands in this yield Lower and Middle Cambrian fossils, including fragments of several species of *Paradoxides*. Then come shales representing the Lingula Flags, and the Shineton Shales with Tremadocian fossils.

A similar succession, but with different local names, is seen near Nuneaton and the Malvern Hills. The Manx Slates of the Isle of Man and the lower part of the Skiddaw Slates of the Lake District may be of Cambrian age.

In the North-West Highlands of Scotland there is a long strip of Cambro-Ordovician rocks, lying unconformably on Torridon Sandstone and covered by overthrust gneiss. The succession starts with quartzites, in part showing vertical worm burrows (Pipe Rock). Then come shales with flattened worm-casts, miscalled Fucoid Beds, and the Serpulite Grit with *Salterella* and *Olenellus*. All these are therefore Lower Cambrian. The succeeding Durness Limestone extends up into the Ordovician, but the fauna is almost entirely different from that of Wales and the Midlands. It is found in the Central States of America, while the Eastern States and New Brunswick yield the Welsh fauna, as also do Scandinavia and Bohemia. The two provinces were probably separated either by a belt of deep water which benthic forms could not cross, though they migrated freely along the coastal belts, or by a land barrier.

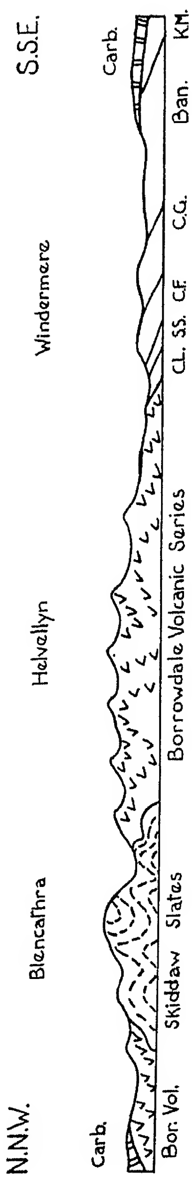

FIG. 168. Structure of the Lake District. Carb—Carboniferous Limestone. KM—Kirkby Moor Flags. Ban—Bannisdale Slates. CG—Coniston Grits. CF—Coniston Flags. SS—Stockdale Shales. CL—Coniston Limestone. Length of section 36 miles.

THE ORDOVICIAN SYSTEM

Ashgillian } Bala
Caradocian }
Llandeilian
Llanvirnian
Skiddavian (Arenig)

These Series are named from Arenig, Bala, Llanvirn and Llandeilo in Wales, Caer Caradoc in Shropshire, and Skiddaw and Ashgill in Cumberland.

In North Wales there is often a basal grit lying unconformably on various members of the Upper Cambrian; and this local break led to the inclusion of the Tremadoc Beds with the Cambrian although their fauna shows many Ordovician elements. The rocks are mainly slates and mudstones, rich in graptolites in places where the slaty cleavage coincides with the bedding planes. There are also coarser greywackes and thin impure limestones, while lavas and ashes are extremely abundant. The volcanic vents appeared in different localities at different times, first at Rhobell Fawr, then Arenig and Cader Idris, and later at Snowdon. Both rhyolites and andesites occur, and it is these, with the massive ashes and intrusive rocks, that form the fine mountains and crags of the

Ordovician outcrops. Slates and greywackes yield tamer scenery, as in Mid and South Wales.

In Shropshire there is a good development of Ordovician rocks west of the Longmynd, but only the upper beds occur in the Caradoc area to the east. The basal quartzite forms the long ridge of the Stiperstones, standing well above the Shineton Shales to the east and the Ordovician shales to the west, and with outstanding crags like the Manstone and the Devil's Chair. Volcanic ash is widespread, and lead and zinc ores occur in the Mytton Flags which overlie the Stiper Quartzite.

In the Lake District the Upper Skiddaw Slates are of Arenig (or Skiddavian) age, but the lower part may be Cambrian. The rounded masses of Skiddaw and Blencathra are in these beds. The overlying Borrowdale Volcanic Series (Llandeilian) consists of rhyolites, andesites and tuffs, with green slates formed from volcanic ash. It is in these beds that the finest mountains are carved—Scawfell, Great Gable, Helvellyn, etc. Then comes the Coniston Limestone Series, with the Ashgill limestones and shales at the top.

In the Southern Uplands of Scotland the lowest beds are radiolarian cherts, tuffs and lavas of Skiddavian age. There is then a gap in the sequence, the Glenkiln Shales being of Llandeilian age and the Hartfell Shales Caradocian and Ashgillian. It was in these shales, exposed at Dobb's Linn near Moffat, that the zonal value of graptolites was first demonstrated by Lapworth in 1878. It had been thought that the same graptolites reappeared time after time in a great thickness of strata; but it is the beds themselves that are repeated by isoclinal folding. A further complication is that the Glenkiln and Hartfell Shales, exposed in the cores of anticlines in the Moffat area, are represented by a much greater thickness of coarser sediments at Girvan and along the northern belt, where they were formed in shallow water near land. The lead ores of the Leadhills occur in these Caradocian strata.

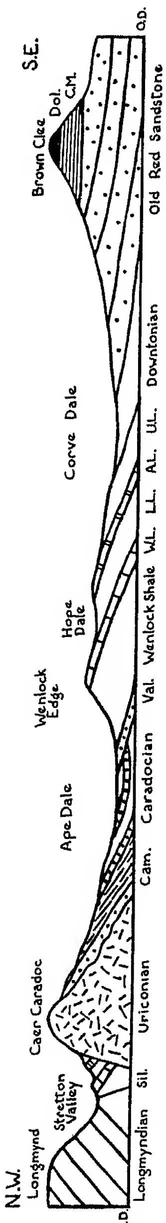

FIG. 169. Structure of Shropshire between the Longmynd and the Clees. Dol—Dolerite. CM—Coal Measures. UL—Upper Ludlow. AL—Aymestry Limestone. LL—Lower Ludlow. WL—Wenlock Limestone. Val—Valentian. Cam—Cambrian. Sil—Silurian. Length of section 11 miles.

THE SILURIAN SYSTEM

Temeside Shales Downton Sandstone	Downtonian
Upper Ludlow Shales Aymestry Limestone Lower Ludlow Shales	Ludlovian
Wenlock Limestone Wenlock Shales Woolhope Limestone	Wenlockian
Tarannon Shales Llandovery Sandstone	Llandoverian (Valentian)

The divisions given above apply to the Silurian of Shropshire, where Murchison first studied the System. Unfortunately it is not a typical area but a shallow-water tract on the flank of the geosyncline. In deeper-water areas the limestones disappear and the shales form a monotonous series, sometimes passing into flags and greywackes, only to be distinguished by their graptolites. Even these died out before the Upper Ludlow Shales were deposited.

Considerable erosion preceded the incoming of the Silurian sea in Shropshire, and the Llandovery Sandstones show overlap among their own members and overstep across the Ordovician and Cambrian on to the Pre-Cambrian rocks at the southern end of the Longmynd. *Pentamerus oblongus* is abundant in places.

The three limestones are found together only in the south, as in the Woolhope dome and the Malvern area, where they form

successive escarpments separated by valleys in the shales. The Wenlock Limestone is the most persistent of the three; it forms the wooded scarp of Wenlock Edge, running from Iron Bridge to Craven Arms, while the Aymestry Limestone forms View Edge to the south-east.

The Ludlow bone-bed is a thin band full of the hard parts of fishes and other organisms. It is followed by yellow sandstones and shales with *Lingula cornea* and *Eurypterus*, which pass up into the Old Red Sandstone.

In Wales the Llandovery Sandstones are found east and south of a line from Llangollen to Llandovery and Haverfordwest; but beyond that line graptolitic shales take their place. The green and purple Tarannon Shale is one of these Valentian shales. But the Ludlovian becomes coarser in North Wales, where the Denbighshire Grits and Flags form a dissected plateau between the Conway valley and the Vale of Clwyd.

In the Lake District the Stockdale Shales are of Valentian age, the Brathay Flags are Wenlockian, and the Coniston Grits and Flags, the Bannisdale Slates and the Kirby Moor Flags Ludlovian. They form the southern part of the district, around Windermere and Sedbergh, with lower and greener hills than the craggy summits of the Borrowdale Series.

Silurian rocks also form the bulk of the Southern Uplands of Scotland, with Ordovician strata exposed in the cores of anticlines. The Birkhill Shales and the conglomerates, grits and shales of the Gala Series are Valentian, and the Wenlockian too shows coarse-grained sediments. The geosyncline was silting up.

LOWER PALÆOZOIC FOSSILS

CAMBRIAN	ORDOVICIAN	SILURIAN
GRAPTOLITES		
Dictyonema sociale	*Phyllograptus typus* *Didymograptus murchisoni* *Diplograptus truncatus*	*Monograptus priodon* *Rastrites maximus*

	CAMBRIAN	ORDOVICIAN	SILURIAN
CORALS			*Heliolites interstinctus* *Favosites gothlandica* *Halysites catenularia* *Omphyma turbinata*
BRACHIOPODS	*Lingulella davisi* *Orthis lenticularis*	*Orthis calligramma*	*Orthis elegantula* *Bilobites biloba* *Leptæna rhomboidalis* *Atrypa reticularis* *Pentamerus galeatus* *P. knighti*
TRILOBITES	*Agnostus pisiformis* *Angelina sedgwicki* *Paradoxides davidis* *Asaphellus homfrayi*	*Ogygia buchi* *Asaphus tyrannus* *Trinucleus concentricus*	*Calymene blumenbachi* *Dalmanites caudatus* *Encrinurus punctatus*
ARACHNIDA			*Eurypterus*

CHAPTER XXVII

UPPER PALÆOZOIC

THE rocks of the Cambrian, Ordovician and Silurian systems mark a period of almost continuous marine deposition longer than any other in our history. It was brought to a close by the silting up of the geosyncline followed by the approach of the two flanks. The strata, which may then have had little more resistance than the Jurassic clays and limestones have to-day, were forced up, thrown into a series of major and minor folds, cleaved, faulted and overthrust; and the gulf in which sedimentation had proceeded for 150 million years gave place to mountain ranges trending N.E.-S.W. along the axis of the trough. They are called the Caledonian chains or Caledonides, since their eroded and re-etched stumps dominate the map of Scotland to this day. In the North-West Highlands and in Mid Wales the trend is N.N.E., and in South Wales nearly due east, but an arcuate form is often seen in modern mountain chains. The folds may have continued into Scandinavia on the one hand and the Acadian chain of North America on the other.

The newly uplifted mountains suffered subaerial erosion and their debris was spread over the intervening low ground as torrent-fans of conglomerate, red and green sands and marls, and lake deposits in which fish remains are the chief fossils. These deposits are called the Old Red Sandstone. Only in Devon and Cornwall do marine Devonian beds crop out, with corals and brachiopods.

Except in a few places like Shropshire there is therefore an intense unconformity at the base of the Old Red Sandstone. And a later movement caused a break, with or without angular discordance, between the Upper and Lower Old Red Sandstone, the Middle Old Red being absent except in North-East Scotland. There was considerable igneous activity in Scotland, which was renewed in Carboniferous times.

The next Period opened with the sea encroaching over the worn-down land surface and depositing the Carboniferous Limestone. Sandy deposits followed, including the deltaic Millstone Grit; and then the Coal Measures, a great thickness of fresh-water deposits with coal seams formed of the debris of rank vegetation. But in Scotland and Northern England coal seams occur in the Lower Carboniferous.

The Coal Measures often overstep the Carboniferous Limestone, and much of the Upper Carboniferous of Europe is missing in Britain. It was at the close of the Carboniferous Period that another important mountain-forming episode occurred. This time the trend was east-west, as seen in the South of Ireland, South Wales and the Mendip Hills. But farther north the movement was at right-angles to this. They are known as the Armorican (or Hercynian) and Malvernian trends. Again the mountains were attacked by atmospheric agents of erosion, and the Permian rocks were formed under desert conditions, except in the east, where a land-locked sea lay.

The Old Red Sandstone is generally barren of fossils, except for a few scattered fish scales. But occasionally, as at Dura Den in Fife, shoals of fish are preserved. These early fish include armoured Ostracoderms like *Cephalaspis*, *Pteraspis* and *Pterichthys*, scaly Ganoids like *Holoptychius* and *Mesacanthus*, and Dipnoi or lung-fishes, such as *Dipterus*, which could survive the drying up of their pools as *Ceratodus* does to-day. *Cephalaspis* is a typical genus of the Lower Old Red Sandstone, *Coccosteus* of the Middle, and *Holoptychius* of the Upper. Some of the fishes were equally at home in sea and lake waters, and so enable us to correlate the marine Devonian with these deposits. A freshwater mussel, *Archanodon*, primitive land plants like *Rhynia* and *Hornea*, and, at a later date, the early fern *Archæopteris*, are other forms sometimes preserved.

In Devon and Cornwall the coeval marine fauna occurs. There are rugose corals like *Acervularia* and *Pachypora*, brachiopods like *Spirifer*, *Atrypa*, *Stringocephalus* and *Rhynchonella*, crinoids, and goniatites.

The marine beds of the Lower Carboniferous are rich in

corals (*Cyathophyllum, Zaphrentis, Lithostrotion*), brachiopods (*Spirifer, Productus*), and crinoids, sometimes with goniatites and orthocerates, polyzoa (*Fenestella*), gastropods, and the last British trilobites. Goniatites are useful fossils in the few marine bands in the Coal Measures; but the usual fossils there are freshwater mussels (*Carbonicola, Anthracomya*) and plants. These include stems of *Calamites, Sigillaria* and *Lepidodendron,* and leaves of *Sphenopteris, Pteropteris* and *Neuropteris.*

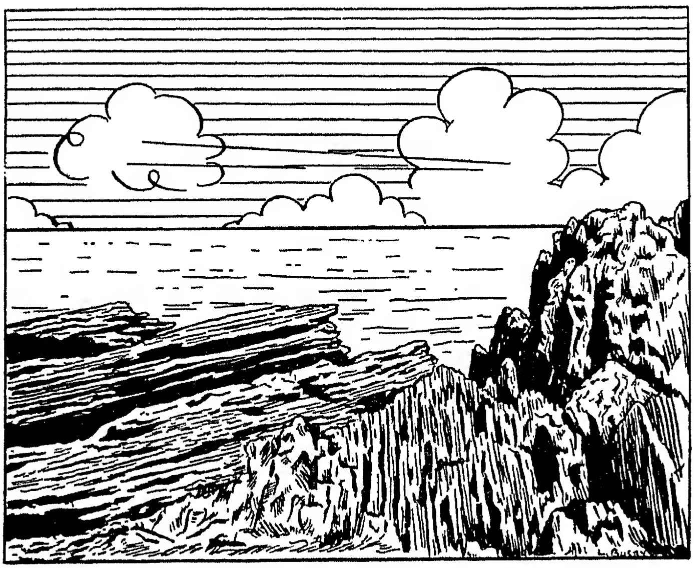

FIG. 170. Unconformity at Siccar Point, Berwickshire. Lower Old Red Sandstone lying on upturned Silurian Rocks.

The Permian fauna is a stunted one that lived in an enclosed sea. *Productus horridus* and *Fenestella retiformis* are the commonest forms.

THE DEVONIAN SYSTEM

In Shropshire, Hereford and Brecon there is no break to mark the close of the Silurian, the red Downtonian passing up into Dittonian or Lower Old Red Sandstone marls and

sandstones, with calcareous concretions known as cornstones. These may be due to the rise of groundwater under desert condition. The Farlovian or Upper Old Red Sandstone rests conformably on the Dittonian but in some places overlaps it on to Silurian rocks. There is little to suggest the great break represented by the absence of the Middle Old Red Sandstone.

In Southern Scotland there is an intense unconformity below the Lower Old Red Sandstone and another below the Upper. Coarse conglomerates, lavas and ashes are strongly developed among the red sandstones. In North-East Scotland the Caithness Flags and John o' Groats Sandstone yield Middle Old Red Sandstone fishes, and the Upper division is poorly represented.

Marine Devonian strata occur south of the Bristol Channel; but associated beds of Old Red Sandstone type in North Devon (Foreland Grit, Hangman Grit and Pickwell Down Sandstone) show that the coast line had no fixed position. The other beds in North Devon are slates and flags, with some lenticular limestones, and their fossils are marine forms such as brachiopods, corals and trilobites. In South Devon and Cornwall sandstones are less developed, the massive limestones of Torquay and Plymouth form attractive marbles when polished, and there is much pillow-lava. The great quarry at Delabole yields roofing slates and also crushed specimens of *Spirifer verneuili* known as Delabole butterflies.

THE CARBONIFEROUS SYSTEM

This is the most important System in Britain, not only in its thickness and extent of outcrop, but in the value and variety of its economic products, which include coal, oil-shale, sandstones, limestones, chert, fireclay, and ores of iron and lead.

Coal Measures	up to 8000 feet
Millstone Grit	,, ,, 3000 ,,
Carboniferous Limestone	,, ,, 3500 ,,

These are convenient lithological divisions, but they are not applicable to all parts of Britain. In Devon and Corn-

wall, for example, the Devonian beds pass up into a series of shales, cherts and grits, with thin seams of poor coal, known as the Culm Measures.

The River Avon below Bristol has cut a gorge through inclined strata from Coal Measures down to Old Red Sandstone, which is the classic section for the Carboniferous Limestone or Avonian; for it was here that Vaughan established a series of zones and sub-zones based on corals and brachiopods. The same zones appear also in the Mendip Hills and South Wales; but most of Wales and the Midlands were still land, and here the Coal Measures rest on Lower Palæozoic rocks or on a thin and sandy representative of the Carboniferous Limestone. North of this land area the limestone is seen again in North Wales and the Pennines, forming craggy scarps in many places and justifying its old name of Mountain Limestone.

In Northumberland the Lower Carboniferous reaches a thickness of 8,000 feet, largely sandstones and shales, with workable coal seams, and with limestones mainly in the upper part. A similar sequence is found in the Central Valley of Scotland, with the addition of oil shales and lavas.

The true Millstone Grit is a deltaic deposit formed by a river from the north. It is best developed in Lancashire and Yorkshire, where the four chief bands of grit separated by shales form such hills as Penyghent and Ingleborough. The grits contain much fresh felspar, and were probably derived from the same source as the Torridon Sandstone. Other arenaceous deposits between the Carboniferous Limestone and the Coal Measures have been termed Millstone Grit, though some of them are of Avonian age and some are later.

The Coal Measures include a great thickness of shales and sandstones, with occasional coal seams. They are in the main of freshwater origin, laid down on a subsiding area, but there were marine invasions from time to time and the marine bands, with their distinctive goniatites, are useful horizons for correlating both the Millstone Grit and the Coal Measures. Swamp vegetation growing on the spot, and not mere drifted material, formed the coal seams, as is shown by their wide extent and constancy of thickness, low ash

content, and underlying seat-earths, which contain rootlets and have the characters of exhausted soils. The felspars have been attacked in these seat-earths and the alkalis removed, leaving valuable fireclays and ganisters (high-silica sandstones).

The Coal Measures are preserved in synclines, which seem to have been initiated in Coal Measure times, for the beds thicken toward the middle of the basins. Contemporaneous fault movement is also indicated. These synclines form our coalfields; and in most cases the exposed coalfield can be extended beneath Permian or younger rocks. But the Kent

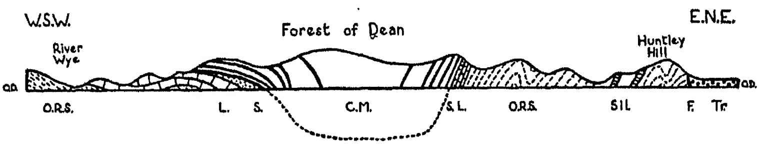

FIG. 171. Structure of the Forest of Dean—May Hill Area. Tr—Trias. CM—Coal Measures. S—Drybrook Sandstone. L—Carboniferous Limestone. F—Fault. Length of section 12 miles.

coalfield is entirely concealed, and the Forest of Dean entirely exposed. On palæobotanical evidence the Coal Measures have been divided into four main groups, viz.:—

Radstockian,	or Upper Coal Measures
Staffordian,	or Transition Series
Yorkian,	or Middle Coal Measures
Lanarkian,	or Lower Coal Measures and Millstone Grit

THE PERMIAN SYSTEM

Toward the close of Carboniferous times the swampy forests gave place to deserts once more; and the fresh mountains of the Armorican folding were eroded to yield the New Red Sandstone (Permian and Triassic) just as the Caledonides had supplied the Old. Red and purple sandstones and shales appear in the Upper Coal Measures of North Staffordshire, and continue almost to the top of the Trias, and the limits of the Permian System are not easy to define.

West of the Pennines the beds are mainly red sandstone, like that of Penrith, with breccias and conglomerates known as brockrams. A Permian flora is preserved locally. East of the Pennines the basal yellow sands are succeeded by the Marl Slate, with fish remains, and then by the Magnesian Limestone. The fauna is a stunted marine one representing life in a shallow enclosed sea of high salinity. Thick salt deposits have been proved in borings.

Certain breccias, sandstones and marls in Devon, the Midlands and Scotland are also believed to be of Permian age.

UPPER PALÆOZOIC FOSSILS

Devonian	Carboniferous	Permian
Corals		
Cyathophyllum helianthoides	*Cyathophyllum regium*	
Acervularia goldfussi	*Caninia cylindrica*	
Pachypora cervicornis	*Zaphrentis spp.*	
Calceola sandalina	*Lithostrotion basaltiforme*	
	Lonsdaleia floriformis	
Polyzoa		
		Fenestella retiformis
Brachiopods		
Spirifer verneuili	*Martinia glabra*	*Productus horridus*
Athyris concentrica	*Spirifer striatus*	
Stringocephalus burtini	*Productus giganteus*	
Rhynchonella cuboides	*Orthis resupinata*	
Terebratula elongata	*Rhynchonella pugnus*	
	Terebratula hastata	
Bivalved molluscs		
Archanodon jukesi	*Carbonicola aquilina*	*Schizodus obscurus*
Univalves		
	Bellerophon costata	
	Euomphalus pentangulatus	
Cephalopods		
Clymenia lævigata	*Orthoceras spp.*	
Manticoceras intumescens	*Gastrioceras listeri*	
Tornoceras retrorsum	*Goniatites sphæricus*	
Trilobites		
Phacops latifrons	*Phillipsia gemmulifera*	
Bronteus flabellifer		

CHAPTER XXVIII

MESOZOIC

THE Triassic, Jurassic and Cretaceous rocks commonly lie almost horizontally above steeply dipping Palæozoic strata; but in the extreme south of England they may themselves be vertical. The Mesozoic Era was free from mountain-forming episodes and from volcanic activity; and in its course the old mountain chains were worn down and the land surface degraded to very low relief. There are many breaks in sedimentation, but even where the hiatus is great, Cretaceous on Trias for example, there is no glaring discordance. The deposits are mainly clays and fine sands, with some limestones, laid down in shallow seas on the continental shelf, or in lake basins or deserts. The Era began with the minimum extension of the seas in the Trias; and it ended with their maximum extension at the time of the Upper Chalk.

Most of the genera of Palæozoic corals and brachiopods had become extinct, and *Terebratula* and *Rhynchonella* are the common brachiopods of the Mesozoic. Lamellibranchs are now more abundant, with *Ostrea, Gryphæa* and *Trigonia,* and gastropods are fairly common. Ammonites and belemnites are the most typical Mesozoic fossils, and the former are useful time markers. Echinoids (*Clypeus, Cidaris, Micraster*) and crinoids (*Pentacrinus, Apiocrinus*) are common at some horizons. Reptiles left their footprints in the Triassic marls, and they dominated land, sea and air in the Jurassic and Cretaceous, with such forms as *Cetiosaurus, Iguanodon, Ichthyosaurus, Plesiosaurus* and *Pteranodon. Microlestes* is a primitive mammal from the Rhætic or Lias, and *Archæopteryx,* the first bird, comes from the Upper Jurassic of Bavaria. Cycads are the dominant land plants.

THE TRIASSIC SYSTEM

In this country the line between the Palæozoic and the Mesozoic is hard to distinguish, falling in the middle of a series of desert deposits conveniently referred to as the New Red Sandstone. Nor is the threefold division of the German Trias, into Bunter Sandstein, Muschelkalk and Keuper, discernible here. The lower sands are regarded as Bunter and the upper as Keuper, with the marine Rhætic Beds at the very top; but fossil evidence is scanty.

In Devon and Somerset the Bunter starts with the Pebble Beds of Budleigh Salterton, containing well-rounded pebbles largely of Ordovician quartzite of a type found in Normandy and Brittany. Then follow sands and a great thickness of Keuper Marls, with salt and gypsum formed by the evaporation of salt lakes. In the Midlands the Bunter consists of dune-bedded red sandstones and pebble beds; and the Keuper Marls include the salt deposits of Cheshire. The Triassic landscape is being disinterred in Charnwood Forest, and groovings due to the sand-blast of the Keuper desert are seen on the granite of Mount Sorrel, near Leicester. The Triassic outcrop forms much of the Midland Plain and extends northward on both flanks of the Pennines into Scotland.

The red Keuper Marls are succeeded by the Tea-green Marls and then by the Rhætic Beds, which mark the rapid influx of sea water over the desert flats and hollows. These beds are often included with the Jurassic in this country, and indeed their boundary with the Lias is not easy to fix; but in Germany the Rhætic is taken as the highest division of the Trias on palæontological grounds. The lower beds are grey and black shales, with a bone bed near the base containing rolled fragments of reptilian bones, well seen at Aust Cliff on the Severn. The upper beds are marls and limestones, including the landscape marble of Cotham, near Bristol, and the White Lias. The Rhætic Beds have a narrow outcrop from Devon northward to Yorkshire.

The Triassic deserts stretched eastward into Germany, where however a land-locked sea gave rise to a shelly limestone, the Muschelkalk. The Alpine Trias is a truly marine deposit and forms the Dolomite Mountains of South Tyrol.

THE JURASSIC SYSTEM

Upper	Purbeck Beds Portland Beds Kimmeridge Clay Corallian (with Ampthill Clay) Oxford Clay (with Kellaways Rock)
Middle	Cornbrash Great Oolite Series Inferior Oolite
Lower	Upper Lias Middle Lias Lower Lias

The Lias is well exposed in the cliffs of West Dorset, where the White Lias is succeeded by the Blue Lias, with

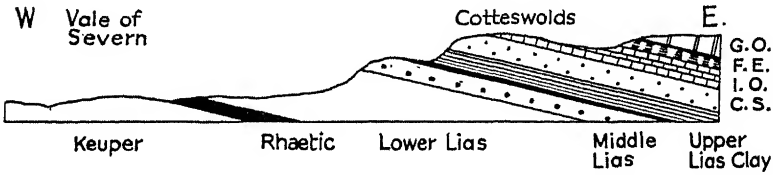

FIG. 172. Structure of the Cotteswold Hills.
G.O.—Great Oolite Series. F.E.—Fuller's Earth Series. I.O.—Inferior Oolite. C.S.—Cotteswold Sand. Length of section 10 miles.

alternations of clay and limestone, followed by clays and fine sands. The Blue Lias and overlying clays continue through much of the outcrop northward, but at the top of the Middle Lias a ferruginous limestone develops, the Marlstone, which forms a shelf below the Cotteswold escarpment and rises to over 700 feet in Edge Hill. The Banbury iron ore is in this Marlstone. In Yorkshire the Lower Lias shales are exposed at Robin Hood's Bay; the Middle Lias includes the Cleveland iron ore; and the Upper Lias is well developed at Whitby, where it yields jet and an abundance of ammonites, "Whitby snake-stones."

The Inferior Oolite is represented in Dorset by the upper part of the Bridport Sand and a thin limestone above it; but it has from 100 to 250 feet of limestone in the Cotteswold

Hills. Farther north a sandy phase sets in, including the valuable Northampton iron ore, becoming calcareous again in the Lincolnshire Limestone. In North Yorkshire the beds are mainly sands of the Lower and Middle Estuarine Series.

The Bathonian stage, or Great Oolite Series, consists in Dorset of the Fuller's Earth Clays followed by the thin limestones and clays of the Forest Marble; but the massive oolitic Bath Stone replaces them near Bath and Minchinhampton.

The Cornbrash is a thin rubbly limestone, rarely more than 15 feet thick, but often forming a distinct feature with a wide dip-slope.

The Oxford Clay is from 300 to 500 feet thick, and in it are the great brick works at Peterborough and Bletchley. The Kellaways Rock and Clay are sometimes present at the base.

The Corallian south of Oxford is partly calcareous (Coral Rag and Corallian Oolite) and partly sandy (Lower and Upper Calcareous Grit). But from Oxford to the Fens it is represented by the Ampthill Clay, with the Calcareous Grit appearing again in Yorkshire.

The Kimmeridge Clay is more than 800 feet thick in Dorset, where certain stone bands in it run out to sea as the Kimmeridge Ledges. It is in part bituminous, and one band of oil-shale is known as Kimmeridge Coal. Where the Kimmeridge, Ampthill and Oxford Clays crop out there is a broad belt of low-lying grass country; and the Fens occupy part of this outcrop.

In Dorset the Kimmeridge Clay passes up into the Portland Sand, followed by the Portland Stone, which includes the famous freestone so familiar to Londoners. The succeeding Purbeck Beds are lagoonal deposits, with gypsum and pseudomorphs after salt crystals in the lower part. Fossil soils (dirt beds) and silicified trees occur in them. Much limestone occurs in the Purbeck Beds, including building stones and the Purbeck marble, which is full of *Viviparus* shells. Both Portland and Purbeck Beds have a discontinuous outcrop owing to the Cretaceous overstep.

Patches of Middle Jurassic beds occur on both the west and east coasts of Scotland; and at Brora a seam of coal is worked in the Estuarine Beds.

JURASSIC FOSSILS

	Lower Jurassic (Lias)	Middle Jurassic (Inferior Oolite to Cornbrash)	Upper Jurassic (Oxford Clay to Purbeck Beds)
Corals		*Thamnasteria arachnoides* *Isastrea explanata*	
Crinoids	*Pentacrinus briareus*	*Apiocrinus parkinsoni*	
Echinoids		*Clypeus plotti*	*Cidaris florigemma*
Brachiopods	*Terebratula punctata* *Rhynchonella tetrahedra* *Spiriferina walcotti*	*Terebratula fimbria* *T. obovata* *Rhynchonella cynocephala*	*Rhynchonella varians*
Bivalved molluscs	*Cardinia listeri* *Leda ovum* *Lima gigantea* *Pecten æquivalvis* *Gryphæa arcuata*	*Astarte obliqua* *Trigonia costata* *Ostrea sowerbyi*	*Trigonia clavellata* *T. gibbosa* *Ostrea delta* *Exogyra virgula* *Gryphæa dilatata*
Univalves		*Pleurotomaria ornata* *Patella rugosa* *Nerinæa eudesi*	*Natica cincta* *Cerithium portlandicum* *Viviparus (Paludina)*
Ammonites	*Dactylioceras commune* *Hildoceras bifrons* *Amaltheus margaritatus*	*Stephanoceras humphriesianum* *Parkinsonia parkinsoni*	*Quenstedtoceras lamberti* *Cardioceras cordatum* *Pavlovia rotunda* *Titanites giganteus*
Belemnites	*Belemnites paxillosus*	*Belemnites giganteus*	*Belemnites oweni* *B. hastatus*

THE CRETACEOUS SYSTEM

Upper Chalk
Middle Chalk
Lower Chalk
Upper Greensand
Gault
Lower Greensand
Wealden Beds

In the south of England the freshwater Purbeck Beds are followed by freshwater Wealden Beds, and the boundary between the two Systems is unsatisfactory. But the Wealden Beds, unlike the Purbeck, are non-calcareous, except for local thin beds of limestone, and without a single marine

FIG. 173.. Wealden Marble with *Viviparus* (*Paludina*).

incursion in all their 2,000 feet of strata. They were formed in a lake stretching from Dorset to the Boulonnais and the Mons area. The Palæozoic rocks beneath the London Basin still formed dry land, but lake deposits occur again near Oxford, where the Shotover Sands yield freshwater shells.

The central part of the Weald consists of the Hastings Sands, rising to 700 feet above sea level in Ashdown Forest and Crowborough Beacon. They include the Ashdown Sand, Wadhurst Clay and Tunbridge Wells Sand, with other more local beds. The formerly important iron industry of the Weald was based on clay-ironstone nodules in the Wadhurst Clay. The Tunbridge Wells Sand in places gives rise to natural crags, as in the High Rocks and the Toad Rock near Tunbridge Wells.

The Weald Clay overlies the Hastings Sand group and forms a belt of low ground all round it, except where cut off by the Channel in the east. There are occasional bands of shelly limestone known as Sussex marble, and the Horsham Stone near the base is a calcareous sandstone used for paving and roofing. Wealden Beds are well seen also in the Isle of Wight and Swanage Bay.

The sea then advanced over the lacustrine flats, depositing the Lower Greensand. The Atherfield Clay at the base is followed by Hythe Beds, in part sandy, in part a chert, or a sandy limestone called Kentish Rag; and it is these hard rocks, where they occur, that form the Lower Greensand

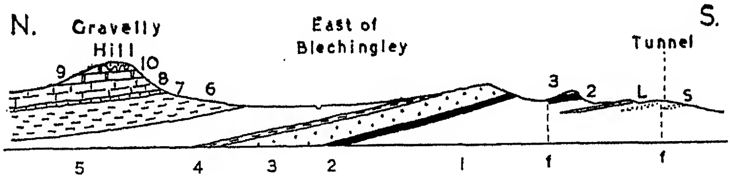

FIG. 174. Section through the North Downs near Caterham, Surrey. Length of section 4 miles.

10 Blackheath Beds.
9 Middle Chalk.
8 Lower Chalk.
7 Upper Greensand.
6 Gault.
5 Folkestone Beds.
4 Sandgate Beds.
3 Hythe Beds.
2 Atherfield Clay.
1 Weald Clay.
L Limestone.
S Sandstone.
f Possible faults.

escarpment seen in Hindhead, Leith Hill and Toys Hill. The next division, the Sandgate Beds, is very variable and includes the fuller's earth deposits of Nutfield and Redhill. The Folkestone Sand at the top is mainly coarse current-bedded sand, in part cemented into an iron-sandstone.

The Lower Greensand is thicker in the Isle of Wight than in the Weald. Beyond the Chiltern escarpment it is largely overlapped by the Gault; but at Faringdon it includes a mass of sponges and other fossils. At Hunstanton the upper part is a brown, ferruginous sandstone called carstone.

The Gault clay forms a low, damp and often wooded belt between the Chalk escarpment and the dip-slope of the

Lower Greensand. It is very fossiliferous in the Warren at Folkestone and at Dunton Green. Westward, more and more of the Upper Gault becomes sandy, often with sponge spicules and a calcareous cement. This is the Upper Greensand, which may form a shelf at the foot of the Chalk escarpment, as at Selborne. The Red Chalk of Hunstanton is of Gault age. The Gault sea was the first to submerge the whole of the Palæozoic ridge below what is now the London Basin; so that many borings in and near London pass from the Gault direct into Old Red Sandstone or Silurian rocks.

After this, terrigenous sediments ceased and calcitic mud was precipitated in a warm and shallow sea that spread over most of England and eastward as far as the Crimea. The sea may have been just too deep for wave action to form oolite grains; instead, we have a soft white limestone, the Chalk, which is often over 98 *per cent.* pure $CaCO_3$. The Lower Chalk and Chalk Marl, however, are less pure, and sandy shore deposits are known in Antrim.

The Chalk covers a wide area in Salisbury Plain, whence it spreads eastward in the North and South Downs, north-eastward in the Marlborough Downs and Chiltern Hills to the Wolds of Yorkshire, and south in Dorset and the Isle of Wight. It is over 1,600 feet thick in the Isle of Wight, and 1,400 feet in Norfolk, but pre-Eocene erosion has reduced it to about 700 feet in the London Basin. Nodules of flint occur, usually in the Upper Chalk, and pyritic nodules are also abundant in places.

CRETACEOUS FOSSILS

Wealden (W.) and Lower Greensand	Gault and Upper Greensand	Chalk
Echinoids		
Peltastes wrighti		*Holaster subglobosus* *Micraster coranguinum* *Conulus conicus* *Echinocorys scutatus*
Brachiopods		
Terebratula sella		*Rhynchonella cuvieri* *Terebratula semiglobosa*

	Wealden (W.) and Lower Greensand	Gault and Upper Greensand	Chalk
Bivalved molluscs	*Cyrena media* (W.)	*Nucula pectinata*	*Spondylus spinosus*
		Inoceramus sulcatus	*Pecten beaveri*
	Exogyra sinuata	*Exogyra conica*	
		Pecten asper	
Univalves	*Viviparus sussexiensis* (W.)	*Dentalium decussatum*	
		Rostellaria carinata	
Ammonites	*Deshayesites deshayesi*	*Hoplites lautus*	*Schlœnbachia varians*
		Hamites maximus	*Turrilites costatus*
			Scaphites æqualis
Belemnites		*Belemnites listeri* (*minimus*)	*Belemnitella mucronata*

CHAPTER XXIX

CAINOZOIC

THERE can hardly be a greater contrast than between the pure limestone of the Chalk and the overlying sands and loams; and the palæontological break is no less striking than the lithological. But there is no obvious angular discordance between the two. The Chalk was gently uplifted and eroded, to a greater extent in the London Basin than in Norfolk or the Isle of Wight; and deposits in Denmark, Belgium and Northern France largely bridge the gap that is so striking here.

The Eocene sands, loams and clays were deposited in the incipient London and Hampshire Basins; and in the latter they pass up into Oligocene beds which are mainly of fresh-water origin. Meanwhile in Antrim and the Inner Hebrides wide sheets of basalt were being poured out by fissure eruptions (Giants' Causeway, Fingal's Cave, etc.), and they were accompanied and followed by intrusive sills, dykes and plutonic masses (Mourne Mountains, Cuillin Hills).

The Miocene is marked, not by any deposits in Britain, but by the folding of the London Basin, the Weald and the Hampshire Basin, as well as the Himalayas, the Alps and the Pyrenees. In South Dorset and the Isle of Wight the Chalk is vertical or slightly overturned in places, and Eocene and Oligocene beds have been almost equally affected.

Pliocene beds have their chief development in East Anglia, and there are small patches on the North Downs, South Downs and Chiltern Hills, and in Cornwall. The Pleistocene saw ice-sheets filling the North Sea and the Irish Sea and covering most of the country north of the Thames and the Bristol Channel. The Holocene or Recent brings us down to the conditions of the present day.

Cainozoic fossils are of special interest in two ways: they show the gradual evolution of modern forms, and they give

evidence of climatic changes, from sub-tropical to glacial. *Nummulites,* an extinct genus of foraminifera, has three species of zonal value in the Bracklesham and Barton Beds. Corals, crinoids, echinoids and brachiopods are not common, but lamellibranchs and gastropods are as abundant and varied as they are to-day. In the Upper Eocene in particular genera like *Conus, Voluta* and *Oliva* suggest a warm sea. The great Mesozoic reptiles were extinct, but the familiar crocodiles and turtles remained, and the first snakes appeared.

The mammals, primitive at first, rapidly developed into ungulates, carnivora, and so on. They had reached their acme before the cold of the ice age killed off many species. The plants, now mainly dicotyledons, also show sub-tropical forms like *Nipa, Aralia* and *Eucalyptus* in the Upper Eocene, while most of the Pliocene flora consists of genera and species still living here.

Further evidence of a warm, moist climate is given by the lateritic weathering of basalt in Antrim, where lava flows had been exposed to the atmosphere for some time before being covered by later outpourings.

EOCENE AND OLIGOCENE

London Basin	Hampshire Basin	
——	Hamstead Beds	M. and L. Oligocene
——	Bembridge Beds	
——	Osborne Beds	
——	Headon Beds	
Barton Beds (Upper Bagshot)	Barton Beds	U. Eocene
Bracklesham Beds (M. Bagshot)	Bracklesham Beds	M. Eocene
Bagshot Sand (L. Bagshot)	Bagshot Sand	L. Eocene
London Clay	London Clay	
Blackheath Beds	——	
Woolwich and Reading Beds	Reading Beds	
Thanet Sand	——	

The variable beds between the Chalk and the London Clay are conveniently grouped as the Lower London Tertiaries. The Thanet Sand is a fine buff loamy sand, used as a moulding sand in iron casting. It is a marine deposit, formed in the lowest part of the London Basin and overlapped by the succeeding beds to the west and south. At the base is about one foot of angular Chalk flints, green-coated, in a glauconitic loam—the Bull Head Bed.

The Woolwich and Reading Beds are marine in East

Kent but estuarine in West Kent and freshwater farther west, where they are largely mottled clays with sands below. In the Hampshire Basin only the Reading Beds occur, except in Sussex outliers, where the estuarine Woolwich type is seen. The Blackheath Beds, sands and pebbles, are confined to Kent and East Surrey.

The London Clay is a blue-grey clay, weathering to brown, 400 or 500 feet thick. It contains large clay-limestone concretions, some of which are septarian, and in some localities it is highly fossiliferous. In places it is covered abruptly by Bagshot Sand, but elsewhere the transition is gradual, with a series of alternating bands of clay and sand called the Claygate beds.

Above the low-lying outcrop of the London Clay, outliers of Bagshot Sand form the hills of Rayleigh, Brentwood, Highgate and Hampstead Heath. The main mass is in the Aldershot-Bagshot area, and here the higher beds are known to be of Bracklesham and Barton age. It is an area of barren heaths, but it has been largely planted with conifers.

It is to the Hampshire Basin that we must turn for the best development of the higher Eocene beds as well as the overlying Oligocene deposits; and they are well exposed in the cliffs from Studland to Hordle, at either end of the Isle of Wight, and in the neighbourhood of Selsey Bill. The

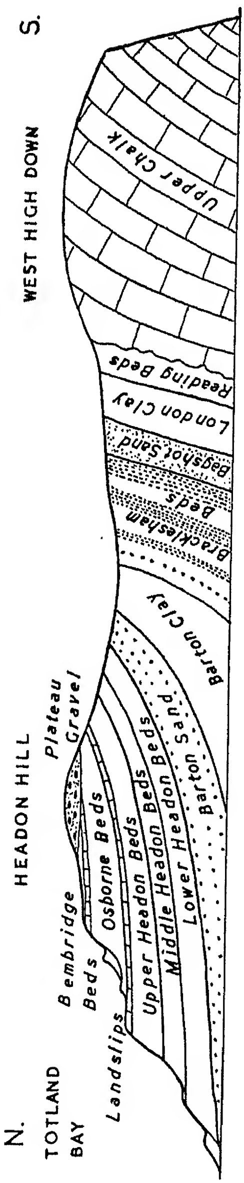

Fig. 175. Section through the West End of the Isle of Wight. Length of Section 1 mile.

London Clay becomes thin and sandy toward the west. The Bagshot Sands around Poole Harbour contain valuable beds of ball clay, and leaf impressions are preserved in some of them.

The Bracklesham Beds start with a thick series of freshwater beds with leaf impressions at Bournemouth, followed by marine sands. They are more fossiliferous, however, at Alum Bay, Whitecliff Bay and the type locality of Bracklesham Bay.

The Barton Beds are well exposed, and full of fossils, in the cliffs east and west of Barton on the Hampshire coast. The upper part is sandy and passes up into the Lower Headon Beds of Hordle Cliff, which are also Eocene though generally included with the Oligocene.

The Oligocene Beds of the Isle of Wight were formed under varying conditions—freshwater, brackish, and occasionally marine. They are highly fossiliferous and are well exposed in the cliffs of the northern part of the Island. They are mainly clays and marls, with some limestones, of which the Bembridge Limestone is the most important and constant.

The Headon Beds are also seen in Hordle Cliff on the Hampshire mainland, and they underlie the gravels of much of the New Forest area. A small outlier of Bembridge Beds caps Creechbarrow in Dorset. Near Bovey Tracey in South Devon a lake basin received masses of sand and clay from Dartmoor, and the associated lignite contains plants of Upper Oligocene age.

PLIOCENE TO RECENT

East Anglia

Holocene	Alluvium
Pleistocene	River Gravels Chalky Boulder Clay Glacial Sands and Gravels. Chalky-Jurassic Boulder Clay Norwich Brickearth Arctic Freshwater Bed
Pliocene	Cromer Forest Bed Weybourn Crag Chillesford Clay and Sand Norwich Crag Red Crag Coralline Crag

The Pliocene deposits of East Anglia are typically lightly-cemented shelly sands known locally as crag. The shells belong to numerous species, and they show a steady dying out of what are now southern and extinct forms and an increase in northern species. The climate was deteriorating, though not yet boreal. The Red Crag is iron-stained, the Coralline and Norwich Crags white or yellow. The Chillesford Beds seem to have been formed in one of the distributaries of the Rhine delta, which at that time occupied part of the North Sea.

Other Pliocene deposits are fossiliferous clays at St. Erth in Cornwall and patches of sand high up on the Chalk of the North Downs, South Downs and Chiltern Hills, which contain Lower Pliocene fossils in sandy ironstone at Lenham, near Maidstone.

In the cliffs between Cromer and Sheringham the Cromer Forest Bed Series is deltaic and contains drifted trees, bones and freshwater shells. It is followed by the Arctic Freshwater Bed and the Contorted Drift, which indicate a much colder climate and are referred to the Pleistocene. But some modern writers would include all the beds down to the Red Crag in the Pleistocene.

The boulder clays, with intercalated glacial sands and gravels, cover much of the country north of the Thames and the Bristol Channel. Near the East Coast they contain rhomb-porphyries and other rocks from Scandinavia, as well as Scottish rocks, Shap granite, fossils from the Jurassic clays, chalk, and flints. Outwash fans from the melting ice-front are seen in the East Anglian Brecklands and on the Chiltern dip-slope.

Glacial lakes and their overflow channels were formed in the Vale of Pickering, Cumberland, Glen Roy, and other places. The valleys of North Wales, the Lake District and the Scottish Highlands were broadened and deepened, their projecting spurs were removed, and cirques and hanging valleys were formed. Perched blocks, *roches moutonnées*, crag and tail, and all the other adjuncts of modern glaciers extend the evidence of glaciation, and so do the patches of marine sand carried far inland.

In Southern England, river gravels are the chief Pleistocene deposits, and they yield flint implements of Palæolithic Man and bones of his mammalian contemporaries. They occur in terraces, of which the lower are the later. Raised beaches too were formed near the coast.

Submergence in Neolithic times accounts for the major areas of Alluvium, such as the Fens. Alluvium, blown sand and shingle deposits are indeed still in course of formation.

The Pleistocene and Holocene were formerly separated from the Cainozoic (Tertiary) under the name of Quaternary or Anthropozoic, because they contain relics of Man. Now that Pliocene Man is generally recognised the distinction has lost its force; and it is more logical to extend the Cainozoic to the present day. Nevertheless, Quaternary is a convenient term at times.

CAINOZOIC FOSSILS

Eocene	Oligocene	Pliocene
Foraminifera		
Nummulites lævigatus		
Worms		
Ditrupa plana		
Polyzoa		*Theonoa aurantia*
Brachiopods		*Terebratula grandis*
Bivalved Molluscs		
Cyrena cuneiformis	*Cyrena obovata*	*Pecten opercularis*
Ostrea bellovacina	*Meretrix incrassata*	*Cyprina islandica*
Mytilus elegans		*Pectunculus glycimeris*
Venericardia planicosta		
Crassatella sulcata		
Chama squamosa		
Univalves		
Melanatria inquinata	*Planorbis euomphalus*	*Littorina littorea*
Turritella imbricataria	*Viviparus lentus*	*Turritella incrassata*
Voluta luctatrix	*Limnæa longiscata*	*Voluta lamberti*
Oliva branderi	*Bulimus ellipticus*	*Chrysodomus contraria*
Fusus porrectus		
Clavella longæva		
Dentalium striatum		

INDEX